

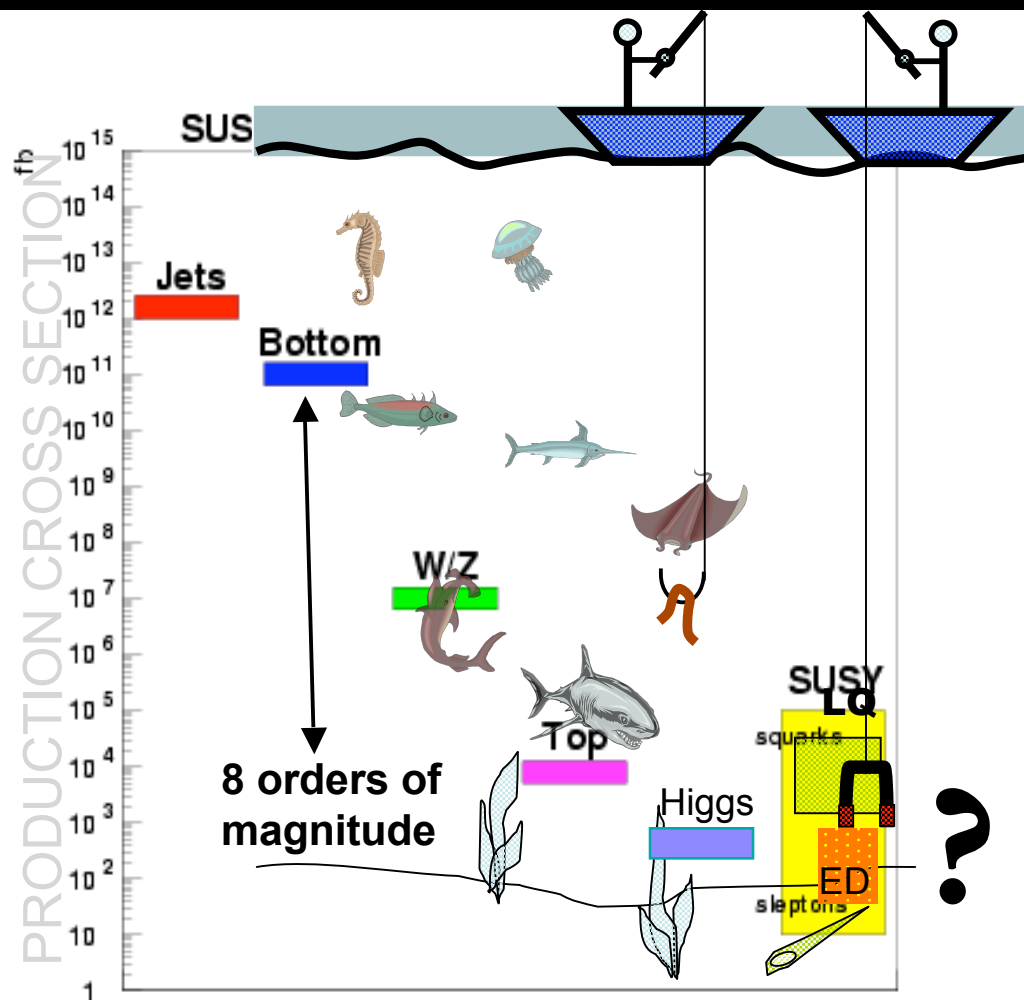
A photograph showing the interior of the Compact Muon Solenoid (CMS) detector at Fermilab. The image captures the complex, circular arrangement of the detector's components, including the solenoid magnet and the various subdetectors. The structure is composed of numerous blue and yellow modules, with a central area where the particle beams intersect. The background shows the industrial environment of the detector's assembly area, with various support structures and equipment visible.

(Brand) New CDF Results for ICHEP'06

Beate Heinemann
for the CDF Collaboration
Wine & Cheese Seminar, FNAL, 07/21/2006

Outline

- Introduction:
 - The CDF detector and it's performance
- The Strong Interaction:
 - Inclusive jet production
 - B-quark production
- The Flavour Sector:
 - Searches for New B-hadrons
 - B_s Oscillations
- Electroweak Symmetry Breaking
 - The top quark
 - The Higgs boson
- Beyond the Standard Model:
 - Supersymmetry
 - Extra Dimensions
 - Model independent searches
- Conclusions



–to Tape: 350k events/hour
 –Top: 2.5 events/hour
 –W/Z+Higgs: ~0.1 event/hour

CDF Probes the Standard Model

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + i\bar{\psi}D\psi \\ & + \psi_i\lambda_{ij}\psi_j h + \text{h.c.} \\ & + |D_\mu h|^2 - V(h) \\ & + \frac{1}{M}L_i\lambda_{ij}^\nu L_j h^2 \text{ or } L_i\lambda_{ij}^\nu N_j\end{aligned}$$

← gauge sector ✓

← flavour sector ✓

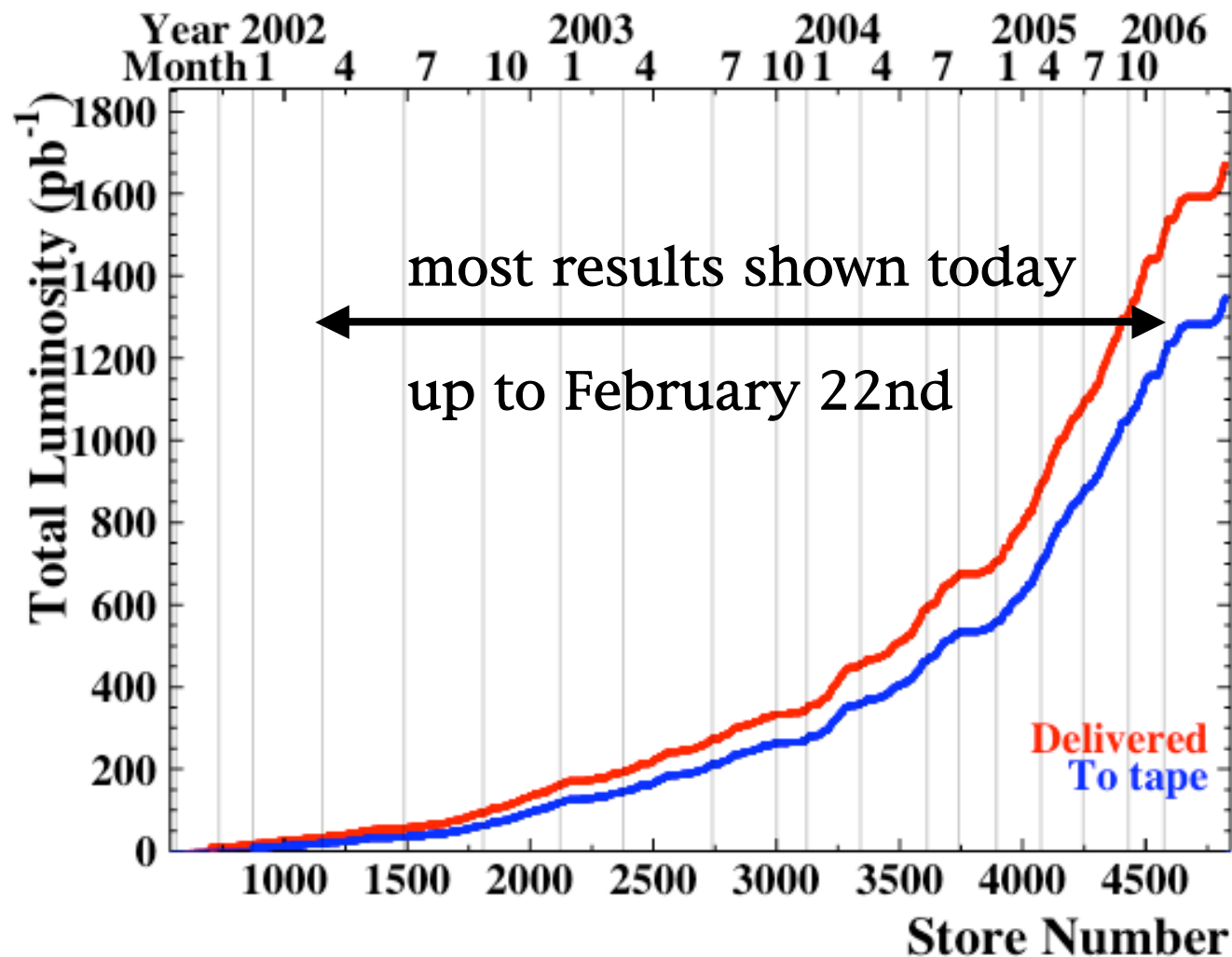
← EWSB sector ✓

← ν mass sector

... and beyond?

supersymmetry (many variants)
extra spacetime dimensions
compositeness
strong electroweak symmetry
breaking
...
something new?!

CDF Luminosity

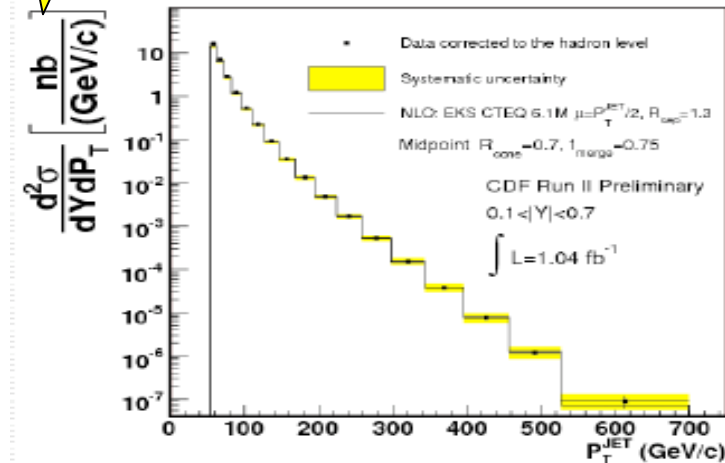


For Physics Analyses: $\int \mathcal{L} dt = 1-1.2 \text{ fb}^{-1}$

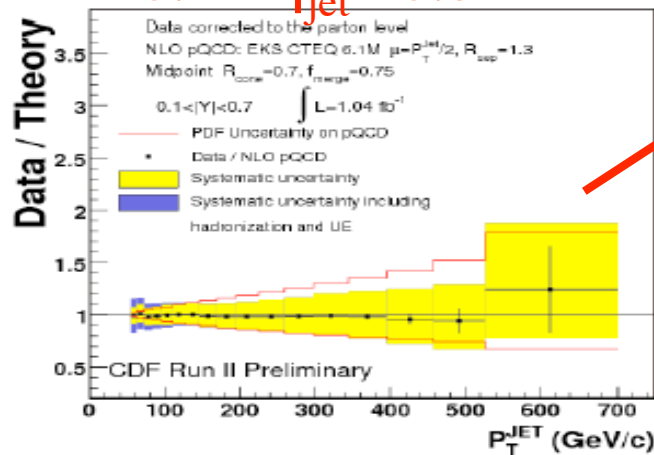
The Strong Interaction

Jets: from Forward to Central

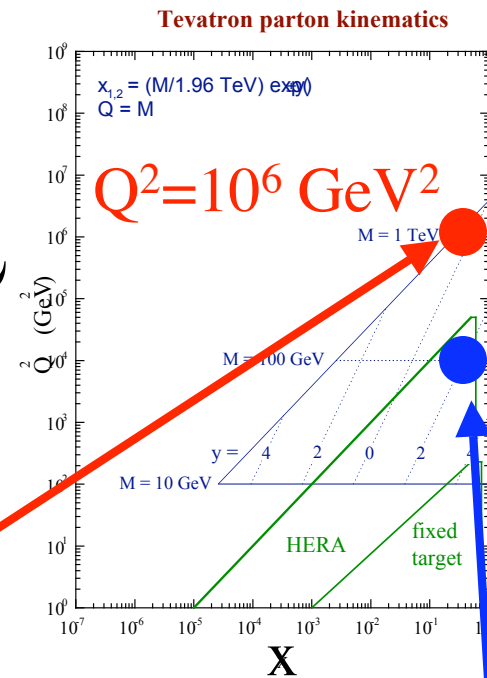
$L=1 \text{ fb}^{-1}$



$0.1 < |\eta_{\text{jet}}| < 0.7$



Q^2 / GeV^2

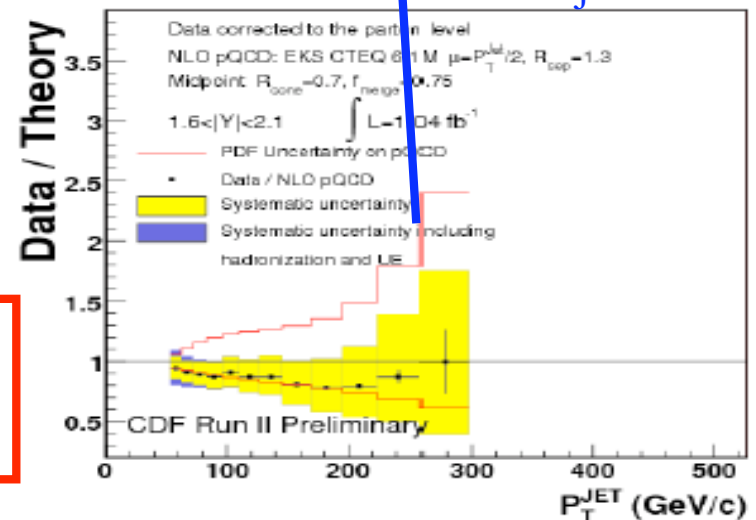


W. J. Stirling

$Q^2 = 10^6 \text{ GeV}^2$

$Q^2 = 10^4 \text{ GeV}^2$

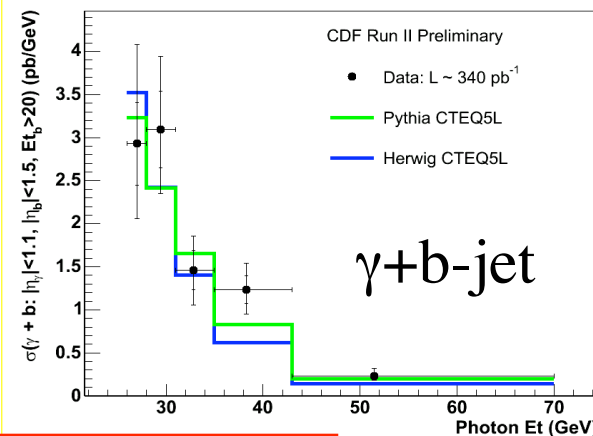
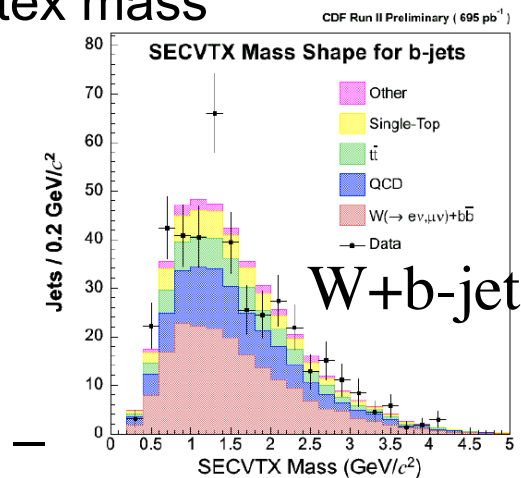
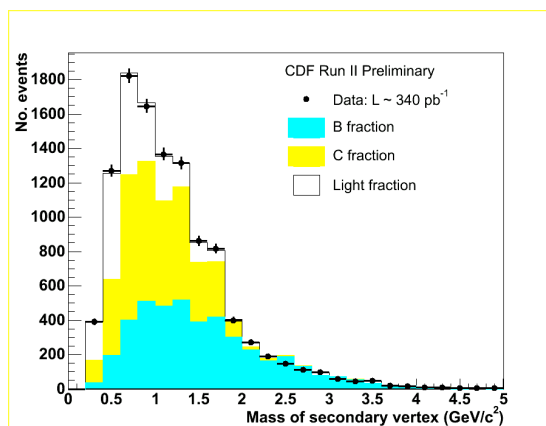
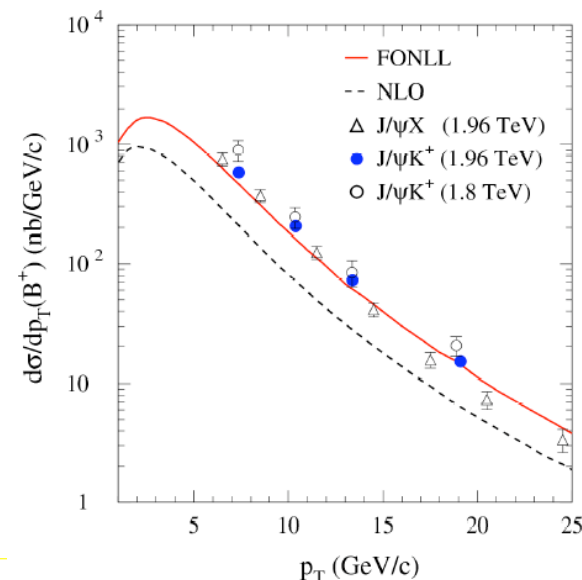
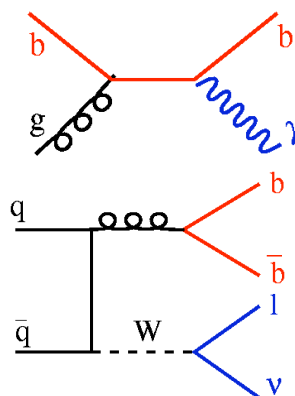
$1.6 < |\eta_{\text{jet}}| < 2.1$



- Forward jets constrain partons at high x
- Central jets probe new physics at high Q^2

B-quark Production

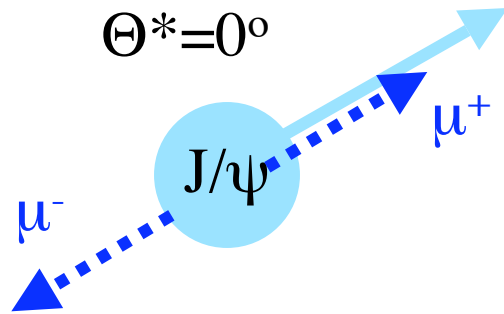
- Run I:
 - data/theory disagreement
- New measurements:
 - B^+ cross section
 - Photon+b-jet, W+b-jet
 - Fit secondary vertex mass



- First measurement of photon+b and W+b jets
- Data agree well with theoretical predictions

E_T

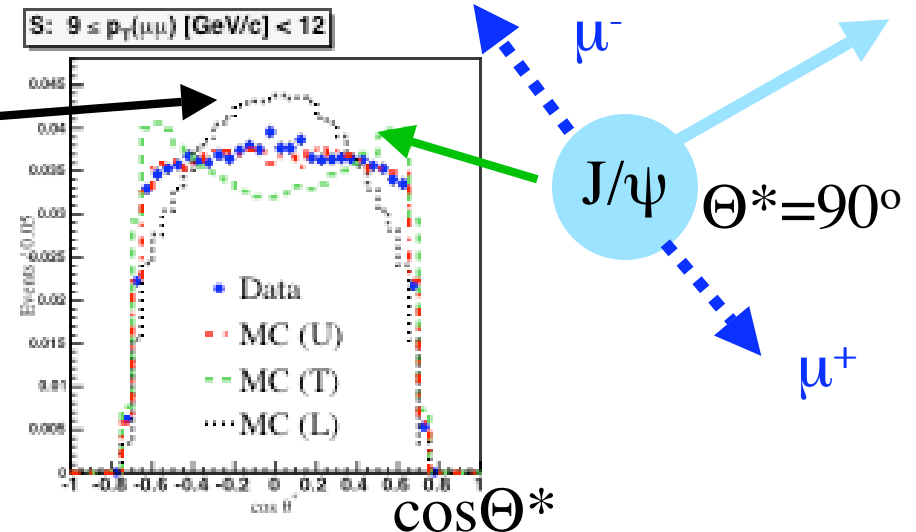
J/ψ Spin Alignment



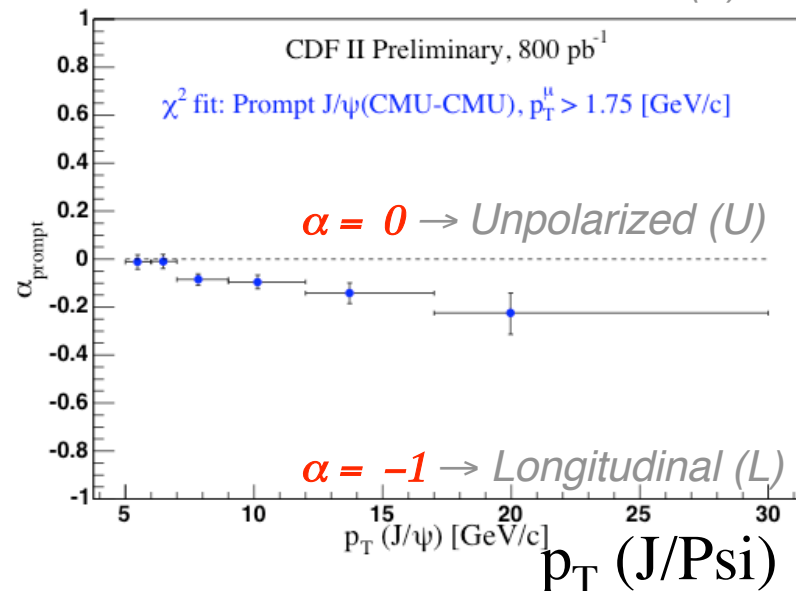
- Do muons decay preferentially into any direction?

- CDF data prefer slight longitudinal polarization:

- Challenges color-octet models
 - NRQCD prefers transverse polarization
- Predicted by Khoze, Martin, Ryskin, Stirling:
 - Eur. Phys. J. C39, 163 (2005)



$\alpha = 1 \rightarrow$ Transverse (T)



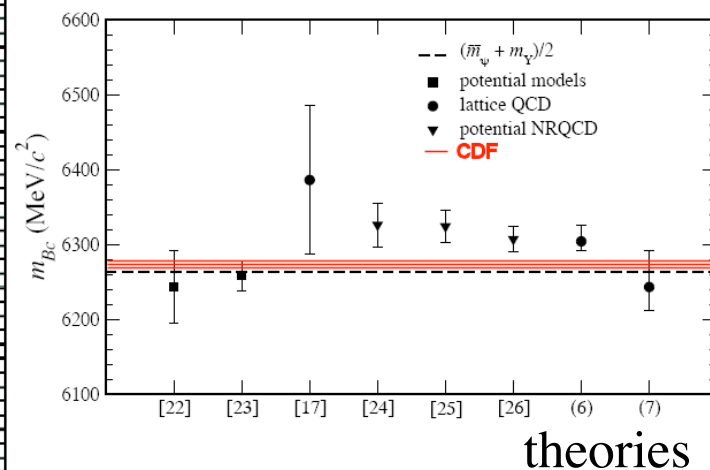
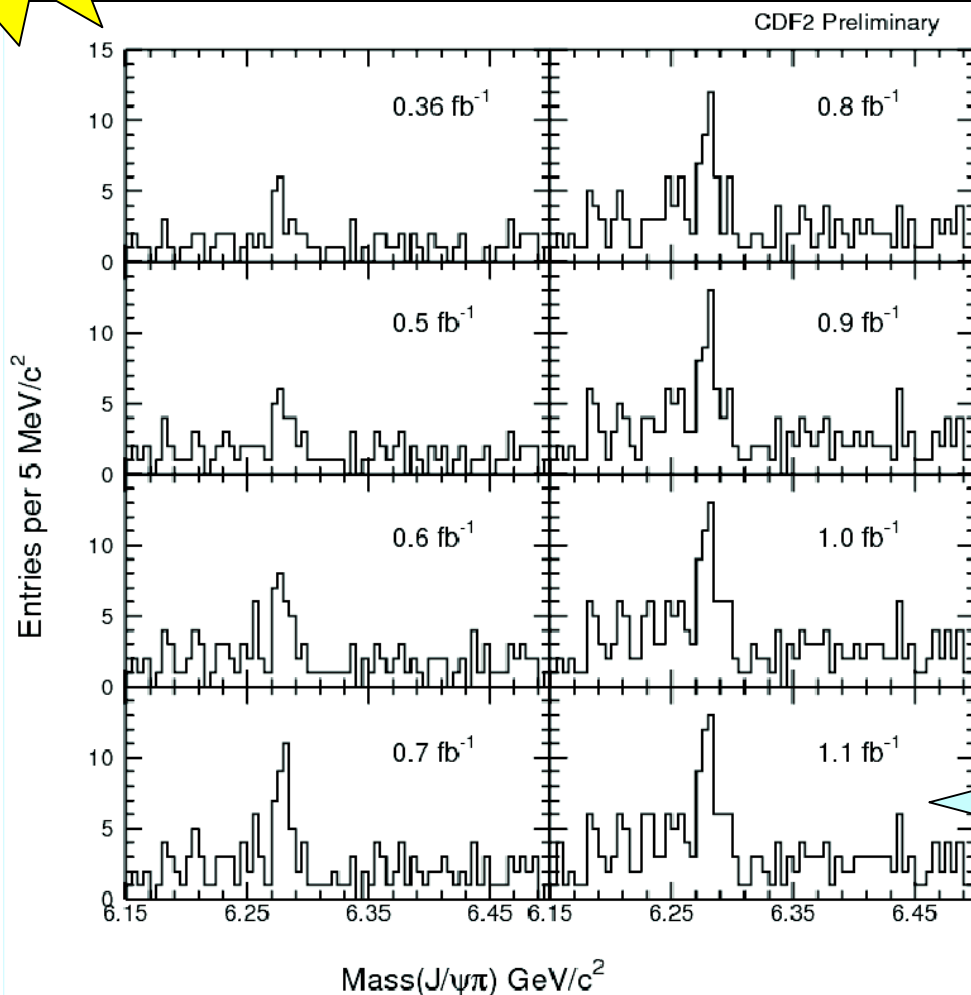
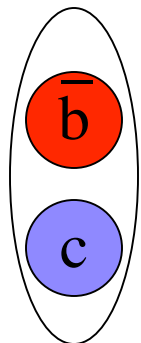
$\alpha = 0 \rightarrow$ Unpolarized (U)

$\alpha = -1 \rightarrow$ Longitudinal (L)

The Flavor Sector

L=1 fb⁻¹

$$B_c^\pm \rightarrow J/\Psi \pi^\pm$$

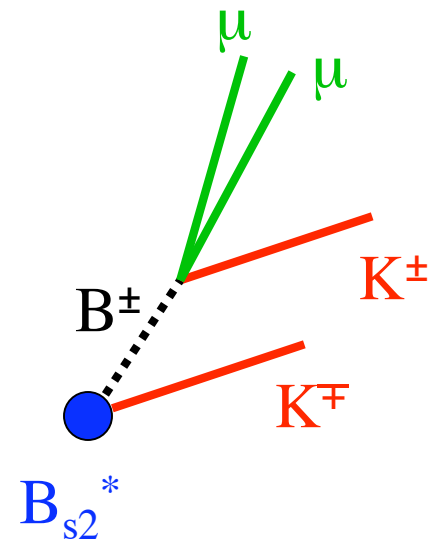
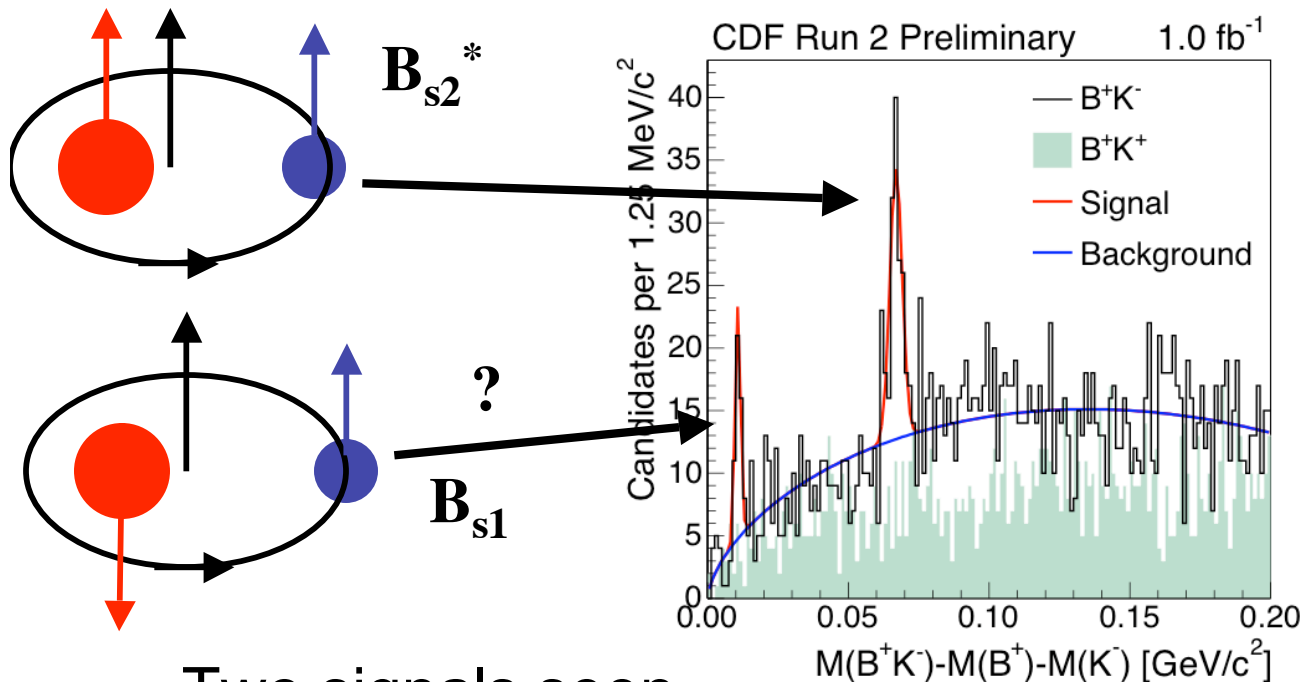


Signal keeps growing!

$$m(B_c) = 6275.2 \pm 4.0 \pm 2.7 \text{ MeV}/c^2$$

Precision measurement challenges theoretical predictions

Orbitally Excited B_s -mesons



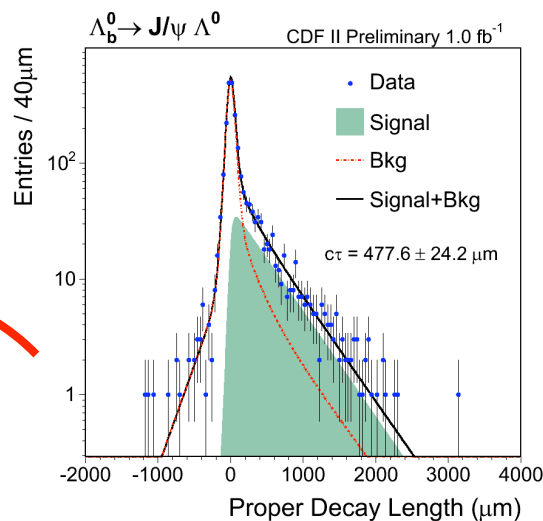
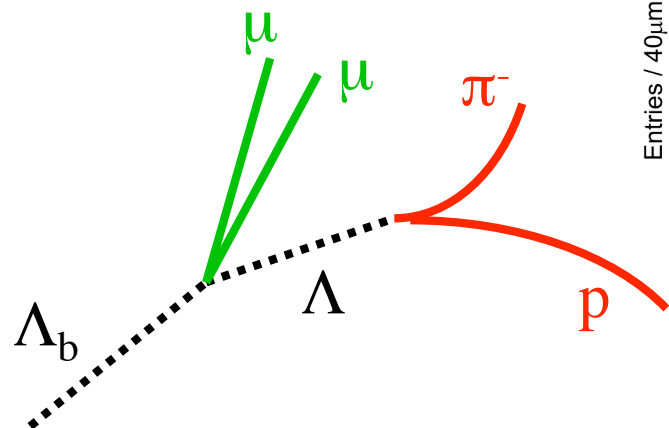
- Two signals seen
 - $B_{s2}^* \rightarrow BK$: 7.7σ , $m(B_{s2}^*) = 5839.7 \pm 0.6$ MeV
 - already seen by OPAL, DELPHI and DØ
 - $B_{s1} \rightarrow B^*K$: 6.3σ , $m(B_{s1}) = 5829.4 \pm 0.7$ MeV
 - Prob. of stat. Fluctuation: 7.3×10^{-6} or 4.4σ
- Mass difference: 10.51 ± 0.45 (stat) ± 0.35 (PDG) MeV

$L=1$ fb⁻¹

First Evidence for B_{s1} state?

L=1 fb⁻¹

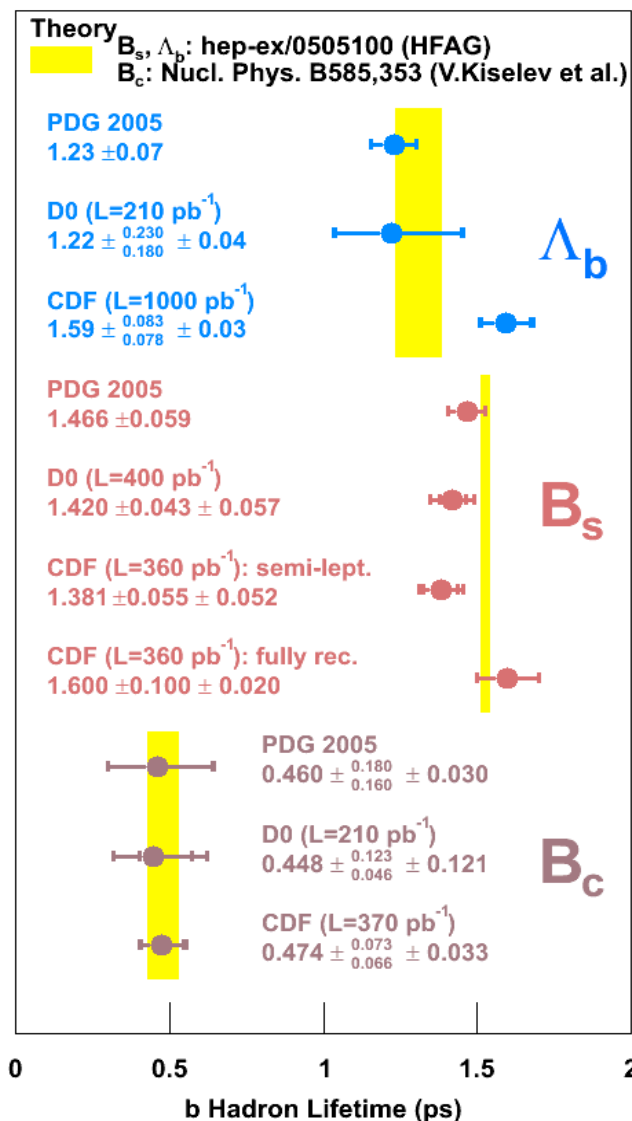
Λ_b Lifetime: $\Lambda_b \rightarrow J/\psi \Lambda$



- Originally lifetime of Λ_b was predicted to be:
 - $\tau(\Lambda_b)/\tau(B^0)=0.94$
- Experimental data (semi-leptonic decays)
 - $\tau(\Lambda_b)/\tau(B^0)=0.84 \pm 0.05$
- CDF Measurement in fully reconstructed decay mode: $\Lambda_b \rightarrow J/\psi \Lambda$

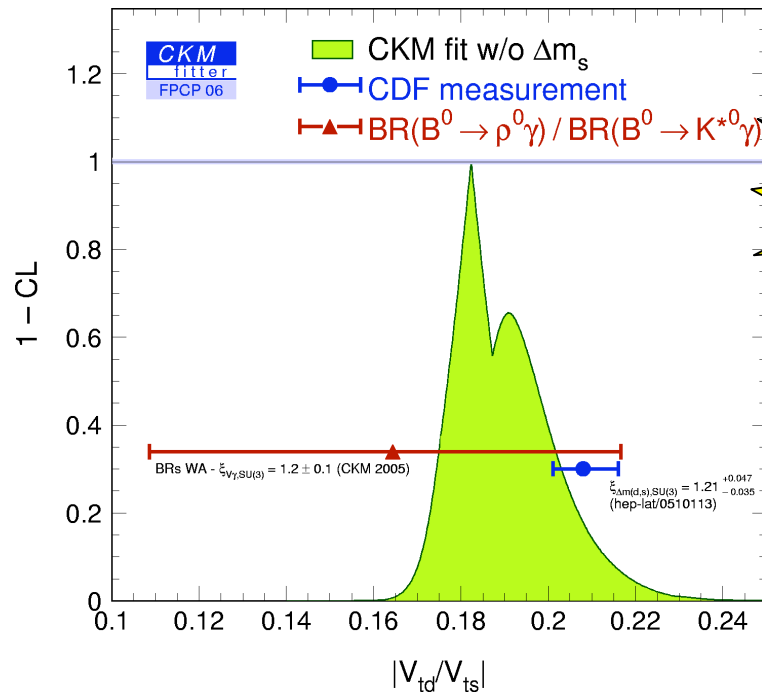
$$\tau(\Lambda_b)/\tau(B^0)=1.037 \pm 0.058$$

- As precise as previous world average
- 3.1 σ different though!

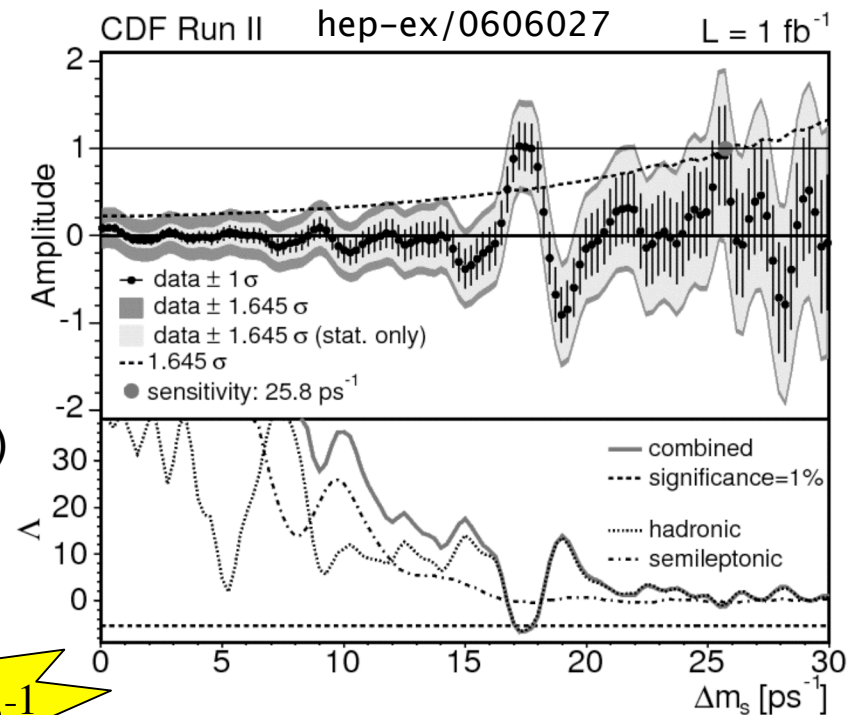


$B_s - \bar{B}_s$ Oscillation Frequency

- Measurement was accepted for publication by PRL:
 - Prob. of stat. fluctuation: 0.2%
 - $\Delta m_s = 17.31^{+0.33}_{-0.17} \pm 0.07 \text{ ps}^{-1}$
 - $|V_{td}/V_{ts}| = 0.208^{+0.001}_{-0.002} (\text{exp}) \quad {}^{+0.008}_{-0.006} (\text{th.})$

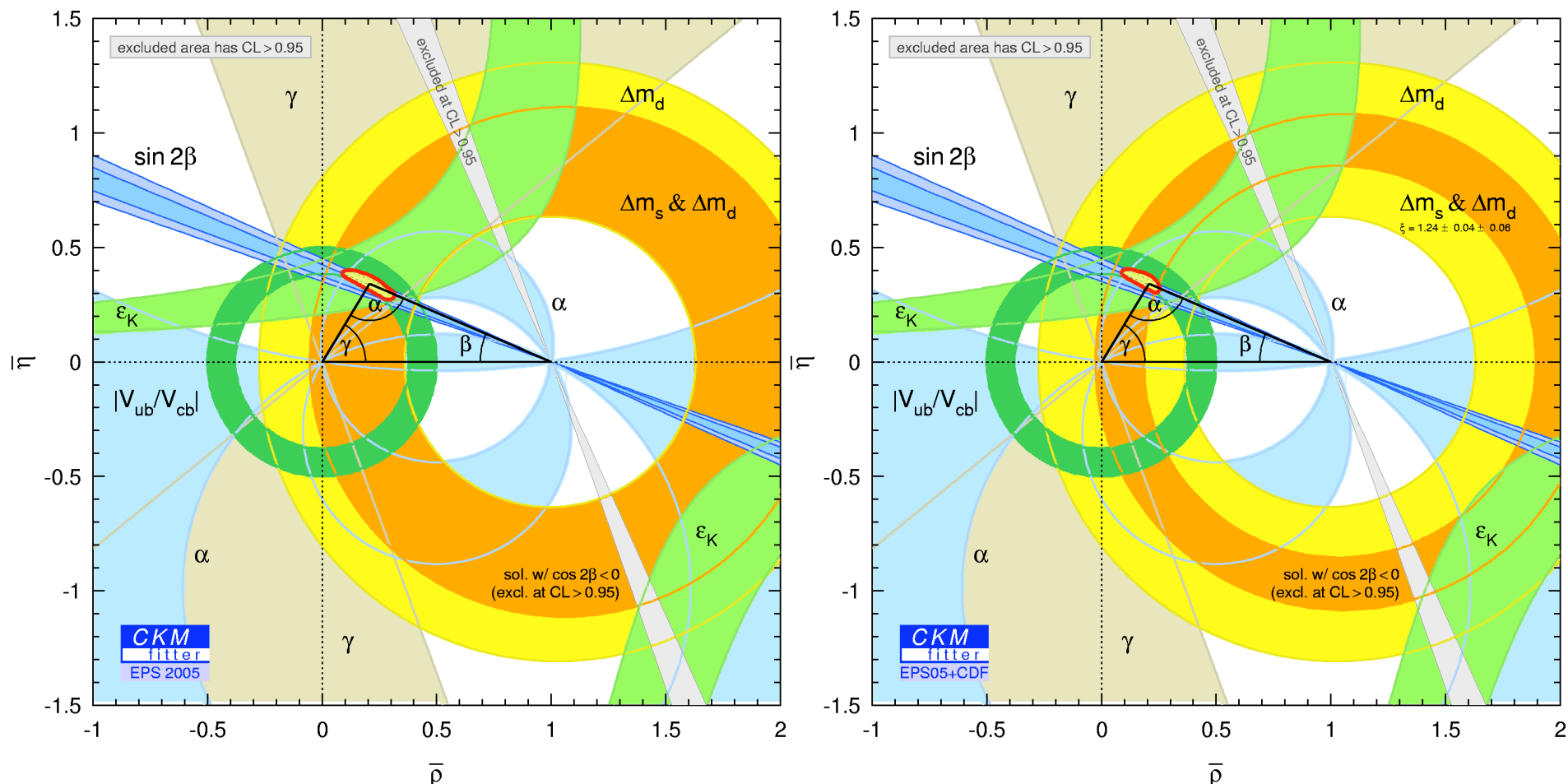


L=1 fb⁻¹



- Measurement consistent with Standard Model prediction
- Severely constrains new physics models

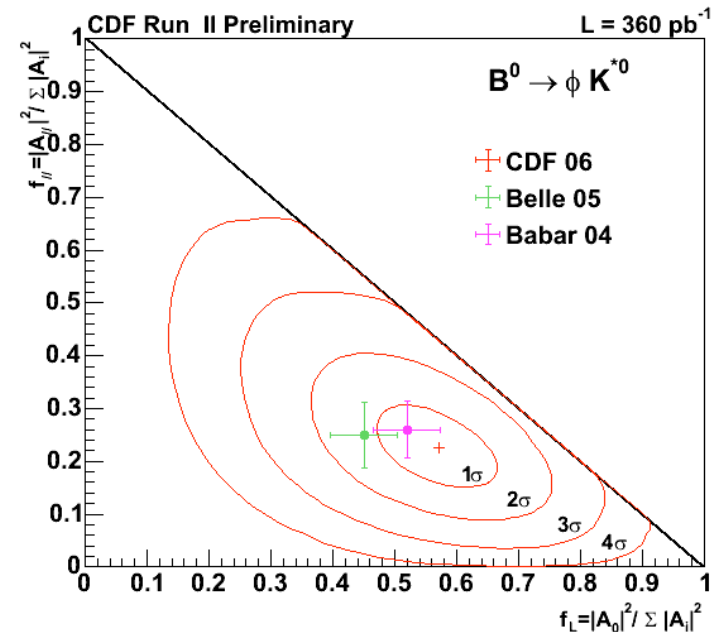
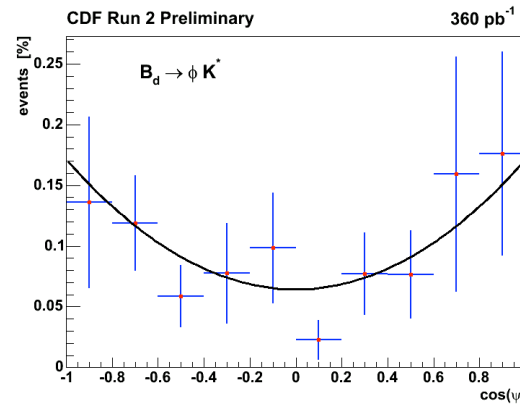
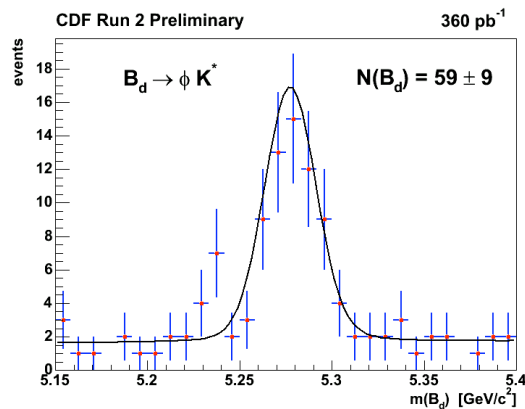
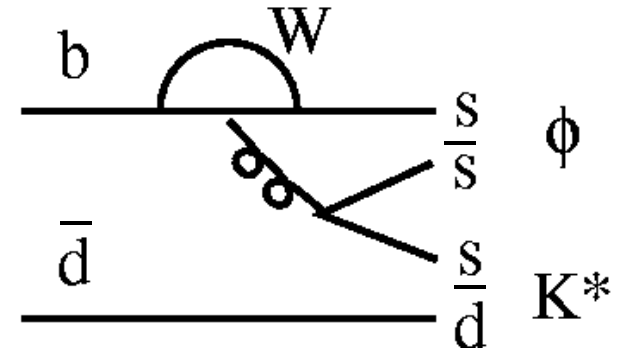
Δm_s measurement: Impact on Unitarity Triangle



Experimental precision on unitarity triangle greatly improved \Rightarrow the triangle still closes!

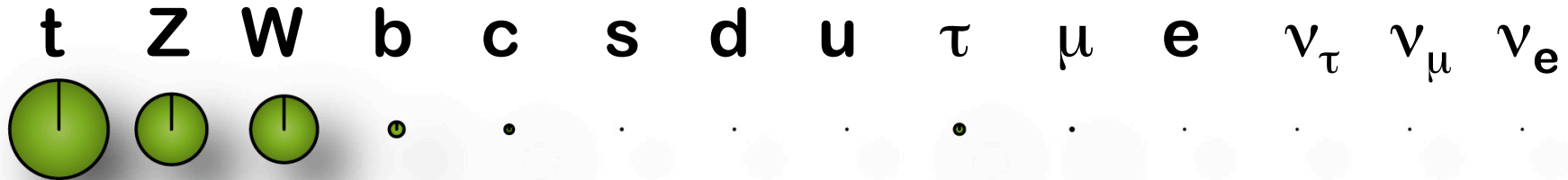
Polarization Amplitudes in $B_d \rightarrow \phi K^{0*}$

- Understand VV decays to facilitate measurements of $\sin 2\beta_s$:
 - $B_s \rightarrow J/\psi \phi$, $B_s \rightarrow \phi\phi$
 - Analogy to $\sin 2\beta$ in $B_d \rightarrow J/\psi K_s$, $B_d \rightarrow \phi K_s$
- Measure polarizations using angular analysis:
 - competitive with Babar/Belle!

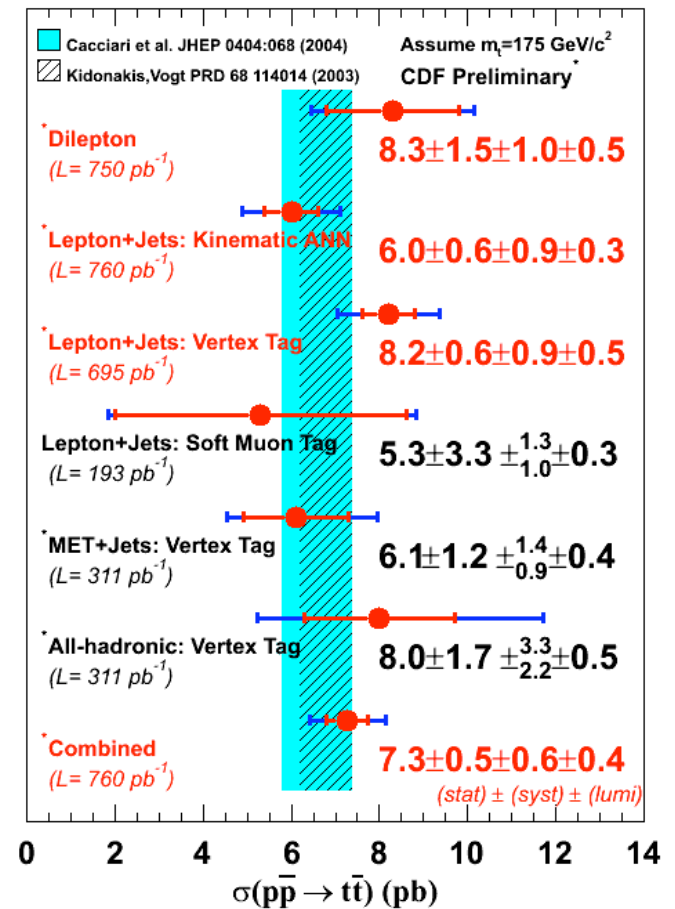
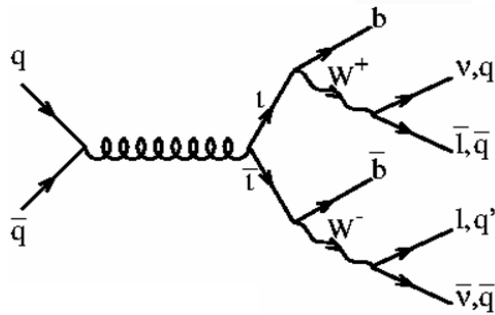


Electroweak Symmetry Breaking

Top Quark Overview

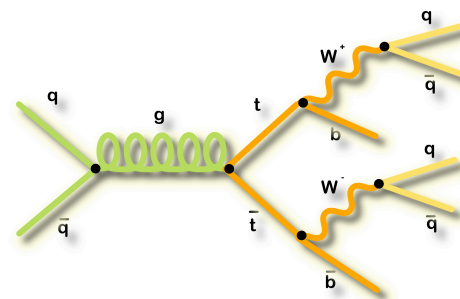


- Standard Model:
 - $\text{BR}(t \rightarrow Wb) \sim 100\%$
 - Cross section: $\sim 7 \text{ pb}$
- Topologies:
 - $tt \rightarrow WbWb \rightarrow qqbbqq$ (44%): all-jets
 - $tt \rightarrow WbWb \rightarrow l\nu bqq$ (30%): lepton+jets
 - $tt \rightarrow WbWb \rightarrow l\nu bl\nu b$ (5%): dilepton
- Measurements:
 - Production rates
 - Properties:
 - **mass**, spin, charge, helicity of W, ...
 - New physics in top events

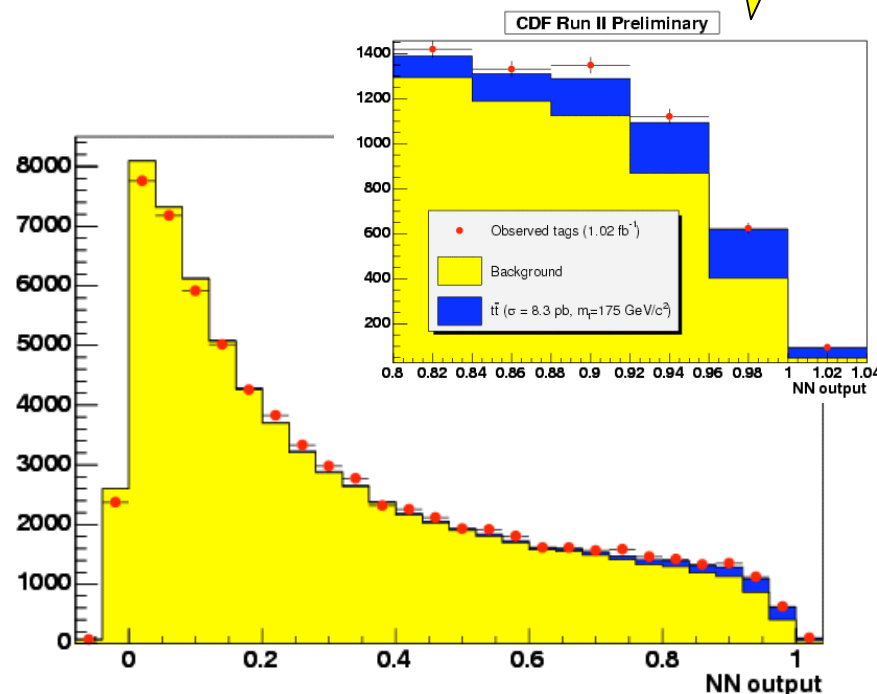
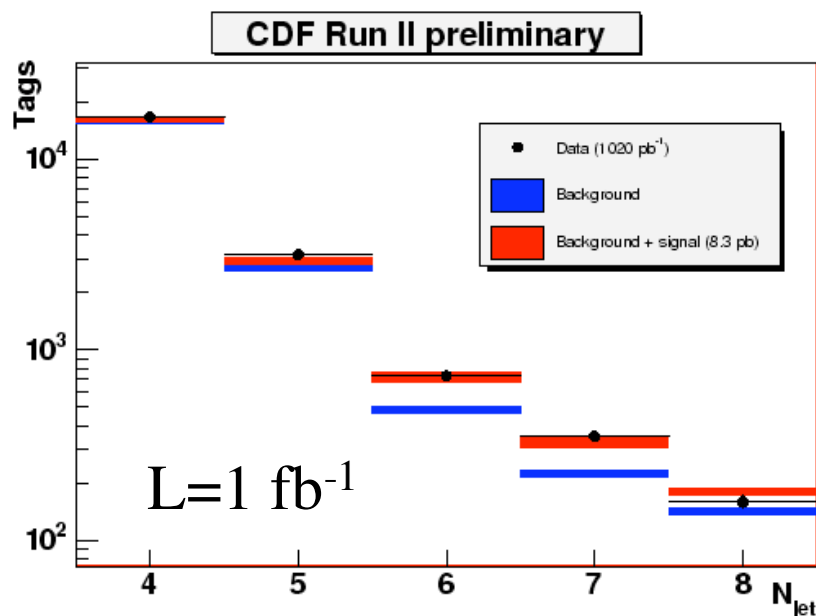


Top hadronic cross section

- NN discriminates between top and multi-jet backgrounds
- Control in pretag sample and 4- and 5-jet bins
- Dominant syst. Uncertainty: JES



$L=1 \text{ fb}^{-1}$



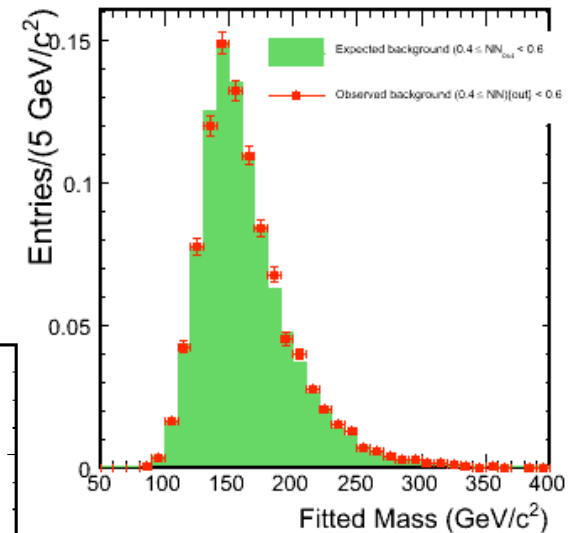
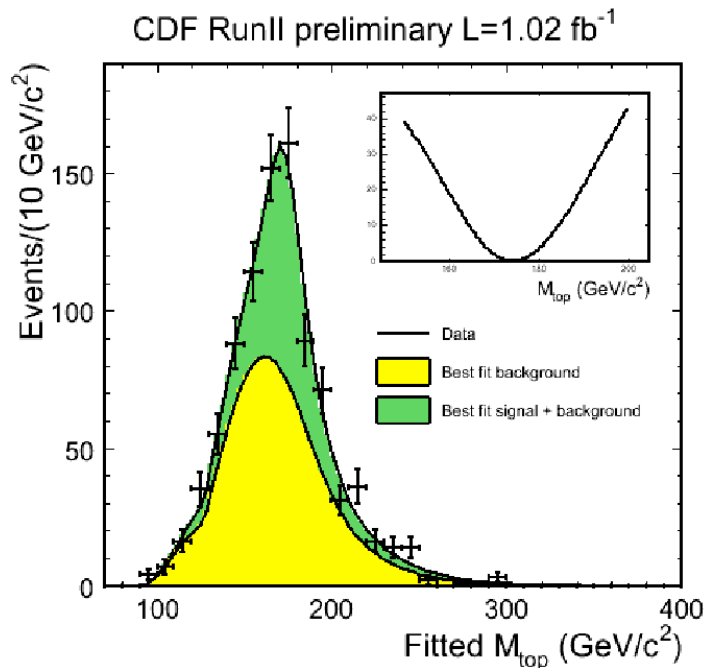
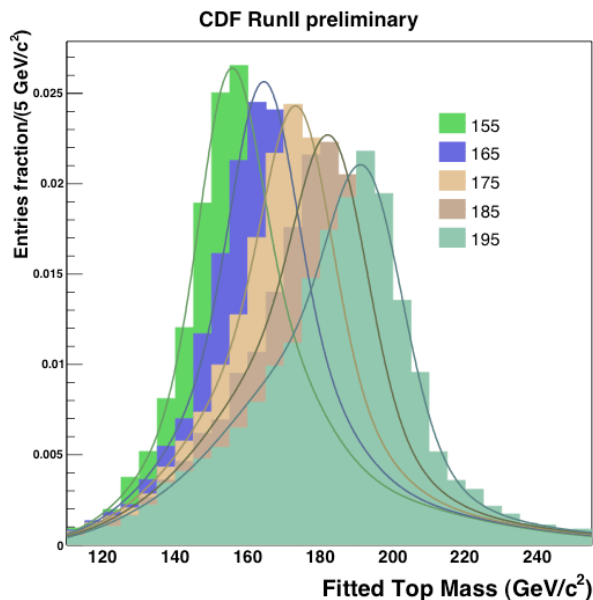
$$\sigma_{t\bar{t}} = 8.3 \pm 1.0(\text{stat})_{-0.5}^{+0.5} (\text{lum})_{-1.5}^{+2.0} (\text{syst}) = 8.3_{-1.9}^{+2.3} \text{ pb}$$

Top Mass: All-jets Final State

- Background control critical:
 - Signal/Background=1/2
 - Background checked in background rich regions
- Templates used for the signal and background shapes

772 events

Background control
 $0.4 < NN < 0.6$



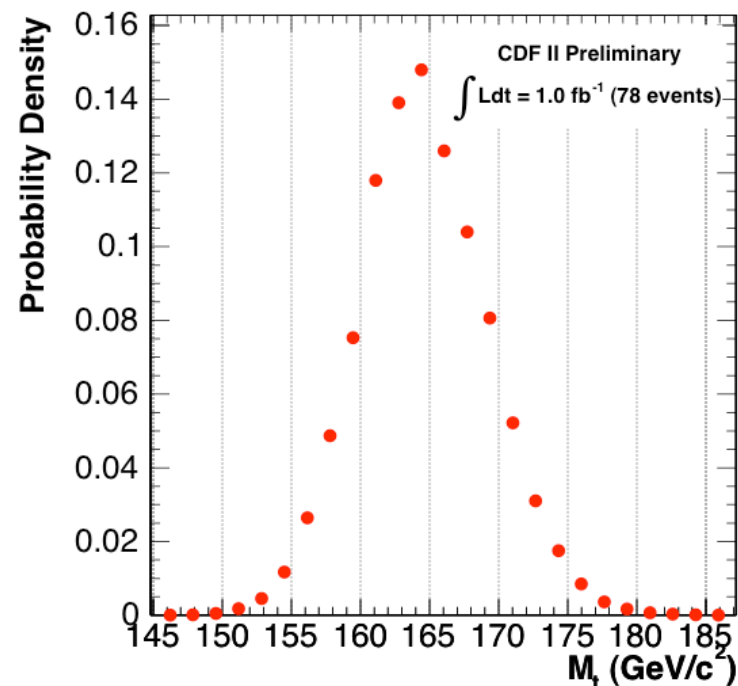
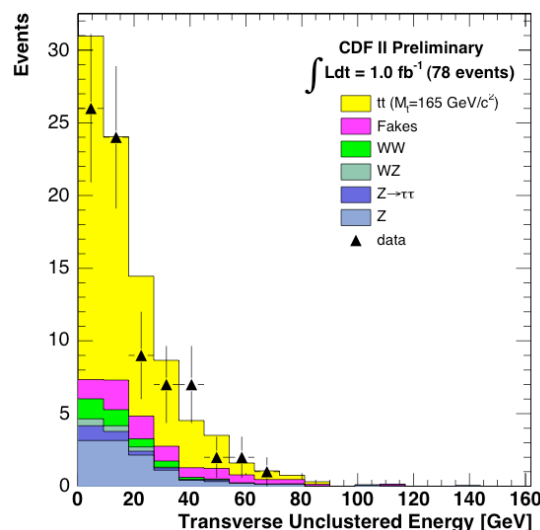
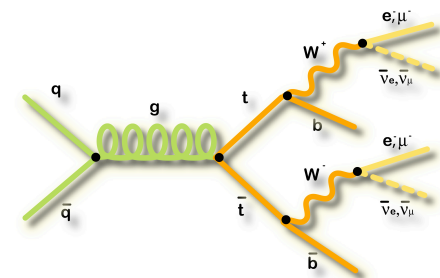
L=1 fb⁻¹

$m_{top} = 174.0 \pm 2.2 \text{ (stat.)} \pm 4.8 \text{ (syst.) GeV/c}^2$

Top Mass: Dilepton Final State

- Improved matrix-element method: 78 events

- ≥ 0 b-tag: Signal/Background=3/2
- ≥ 1 b-tag: Signal/Background=30/1
- New: Measure recoil (p_T of $t\bar{t}$ system) and include this information
 - A priori uncertainty improved by 10%



$L=1 \text{ fb}^{-1}$

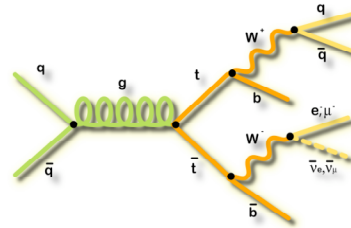
$$m_{\text{top}} = 164.5 \pm 3.9 \text{ (stat.)} \pm 3.9 \text{ (syst.) GeV/c}^2$$

$$\text{with b-tagging: } m_{\text{top}} = 167.3 \pm 4.6 \text{ (stat.)} \pm 3.8 \text{ (syst.)}$$

$L=1 \text{ fb}^{-1}$

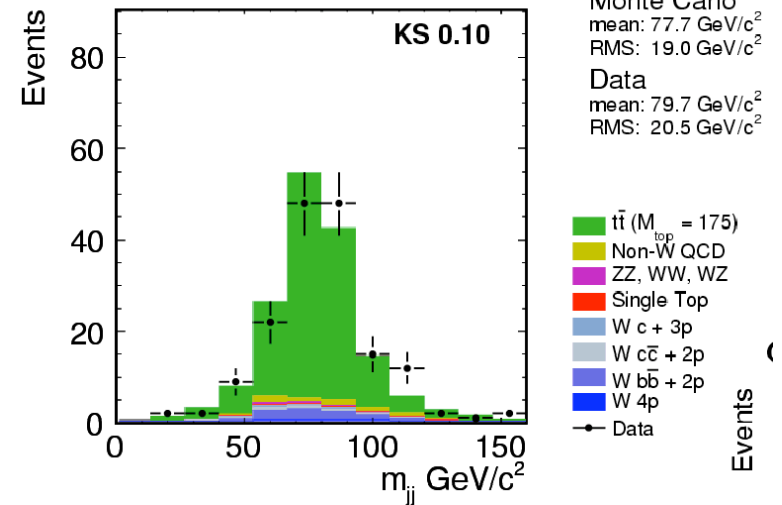
Top mass: Lepton + Jets

166 events

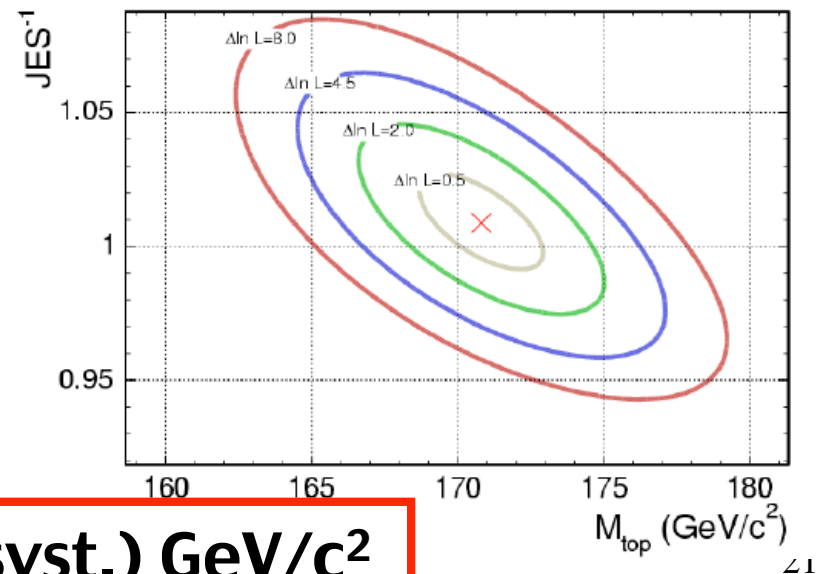


- Matrix-Element method
 - ≥ 1 b-tag \Rightarrow Signal/Background=4/1
 - 1 unknown, 3 constraints
 - Overconstrained!
 - Add jet energy scale as 2nd unknown and fit for it:
 - $\Delta \text{JES} = 0.99 \pm 0.02$
 - Consistent with a priori knowledge
 - Uncertainty only 2%!!!
- Single most precise measurement

CDF Run II Preliminary (955 pb^{-1})

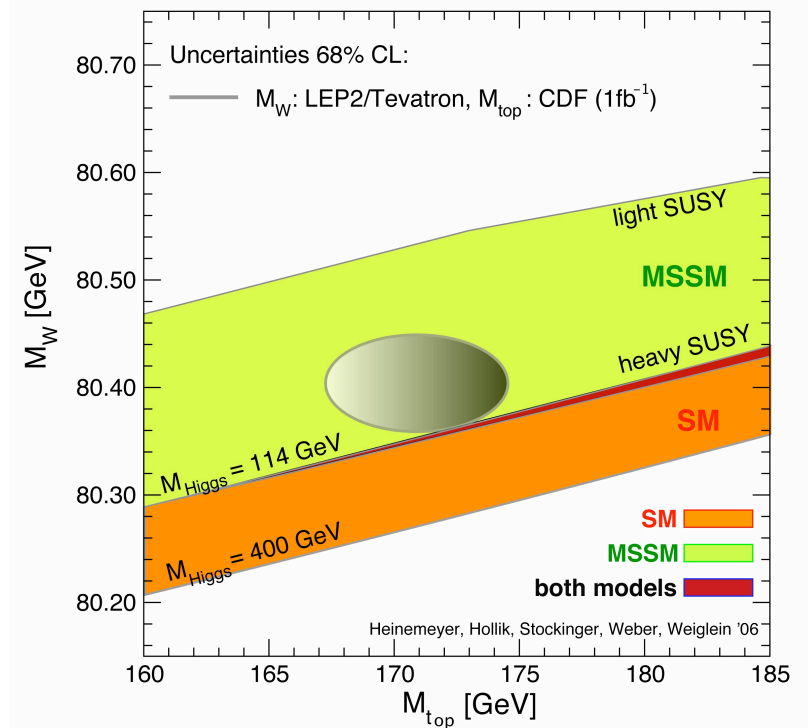
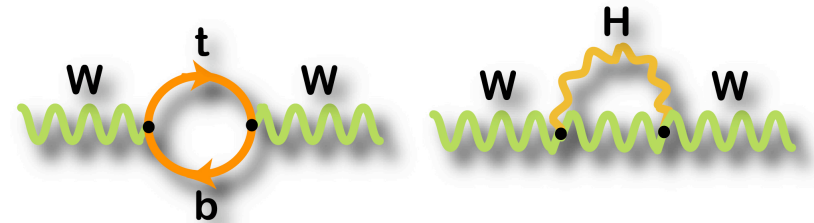
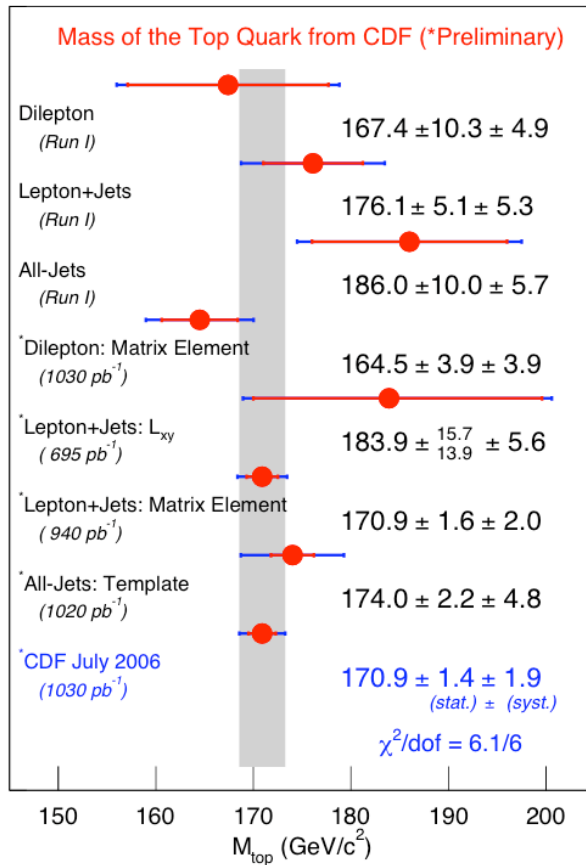


CDF Preliminary 955 pb^{-1}

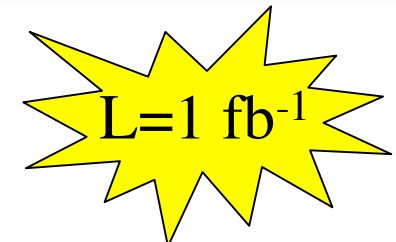


$$m_{\text{top}} = 170.9 \pm 2.2 \text{ (stat.+JES)} \pm 1.4 \text{ (syst.) } \text{GeV}/c^2$$

Top Mass: CDF Combined Result

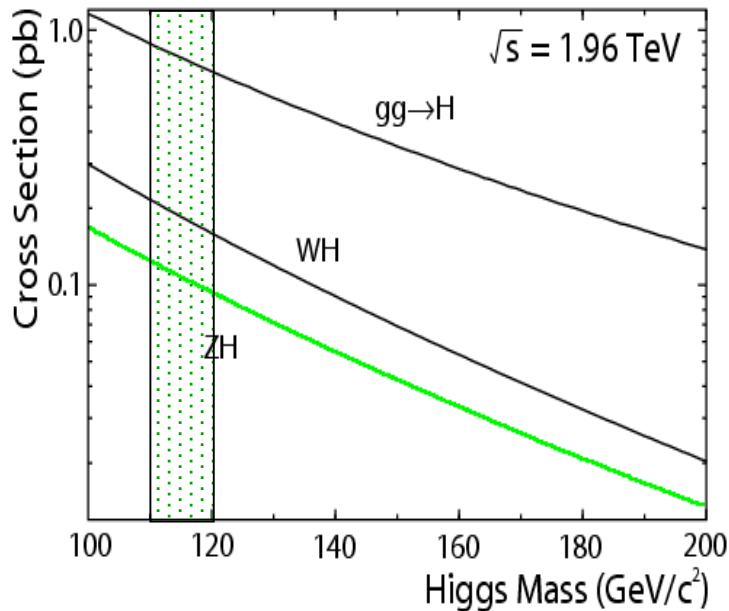


- $m_{top} = 170.9 \pm 2.4 \text{ GeV}$
- Standard Model excluded at 68% CL
 - Perfectly allowed at 95% CL though

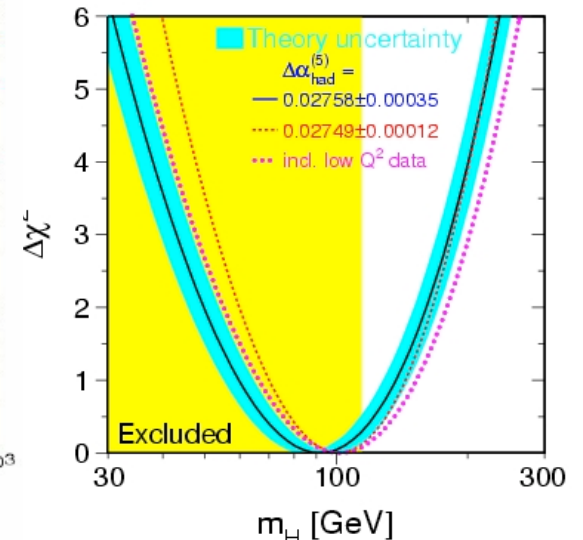
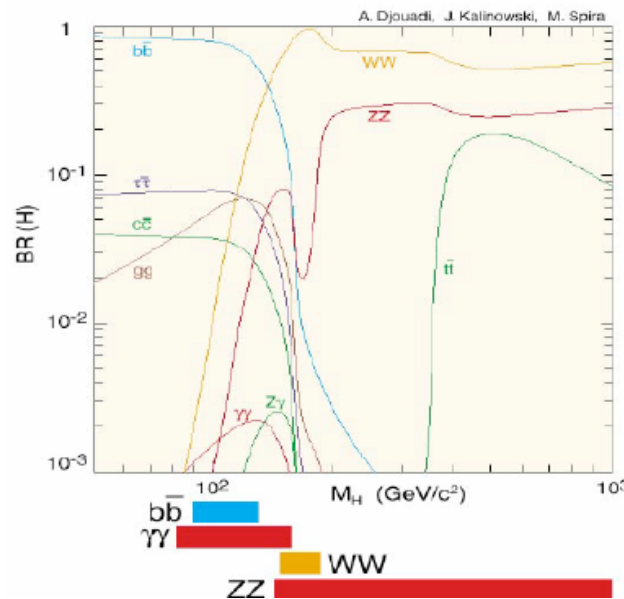


Higgs Boson: Intro

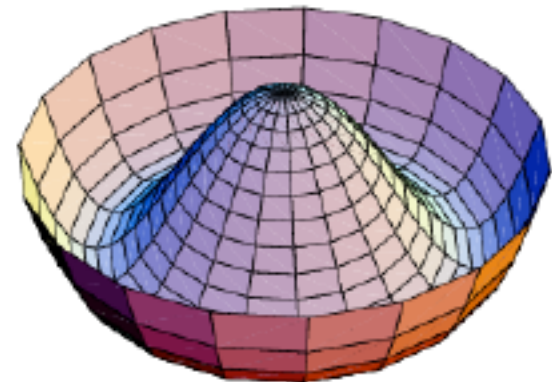
Cross Section



Branching Ratio



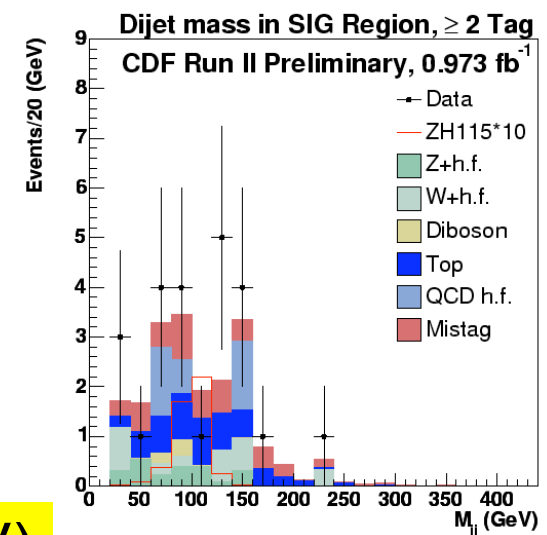
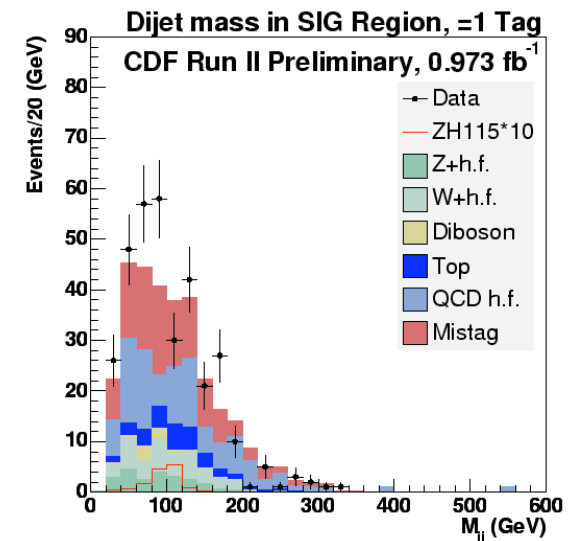
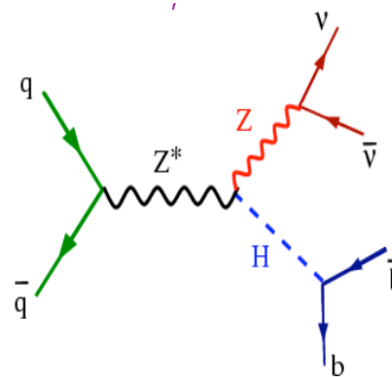
- Today focus on low mass Higgs
 - Preferred by electroweak precision measurements
 - Main analysis modes:
 - **$WH \rightarrow l\nu bb$, $ZH \rightarrow \nu\nu bb$, $ZH \rightarrow llbb$**



$L=1 \text{ fb}^{-1}$

Higgs: $ZH \rightarrow \nu\nu b\bar{b}$

- Signature:
 - 2 b-jets + missing ET
- Many improvements lead to effective luminosity gain of $(S/\sqrt{B})^2=6.3$
 - Improved lepton veto
 - Separate single and double b-tags
 - Include WH as signal
 - Use fit to dijet mass spectrum
- Plus inclusion of full data luminosity:
 - No evidence for deviation from background

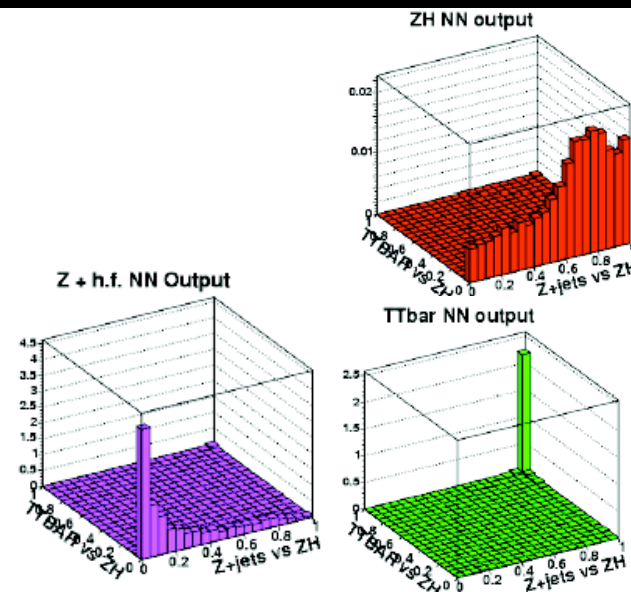
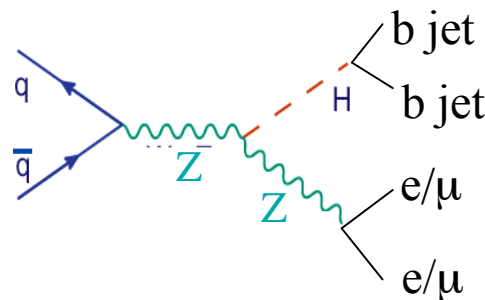


Exp. Limit / SM rate=14.2 (at $m_H=115 \text{ GeV}$)

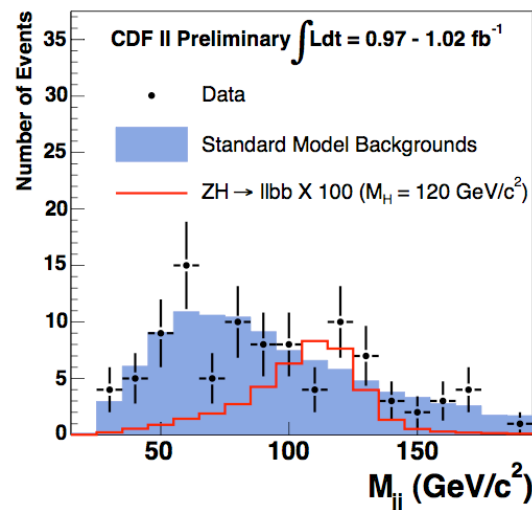
$L=1 \text{ fb}^{-1}$

Higgs: $ZH \rightarrow l\bar{l}b\bar{b}$

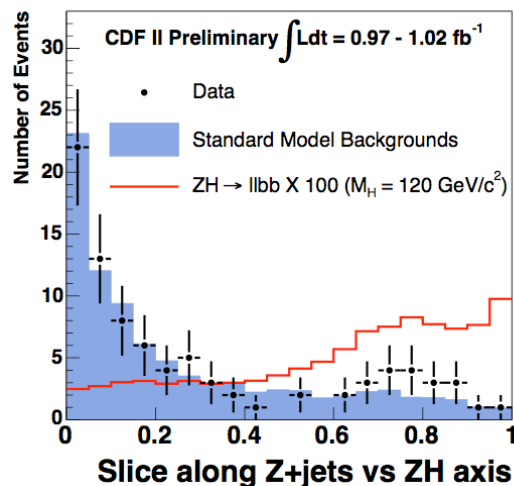
- Strategy:
 - 2 leptons and 2 jets
 - 1 or 2 b-jets
 - Use 2D NN to separate signal from backgrounds:
 - Z+jets, Top, ZZ, WZ, ...



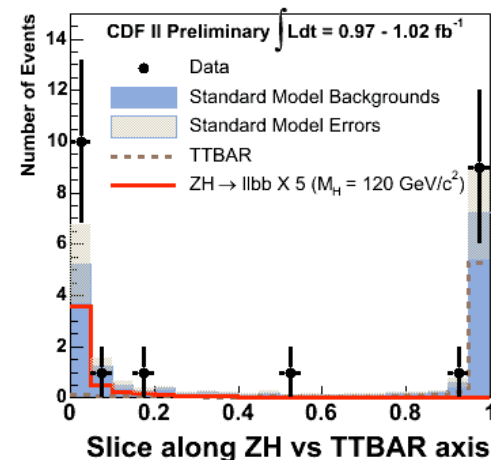
Search for $ZH \rightarrow l\bar{l}b\bar{b}$



Search for $ZH \rightarrow l\bar{l}b\bar{b}$



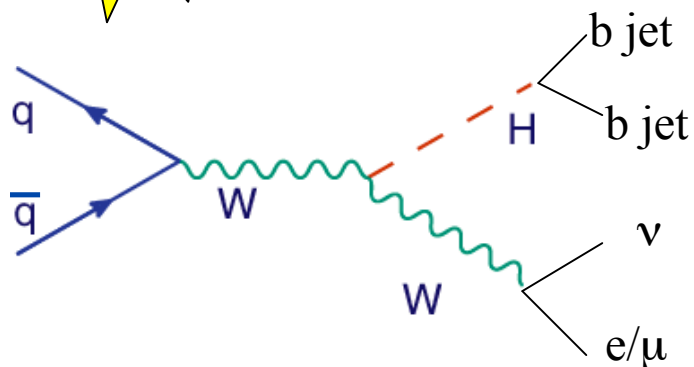
Search for $ZH \rightarrow l\bar{l}b\bar{b}$



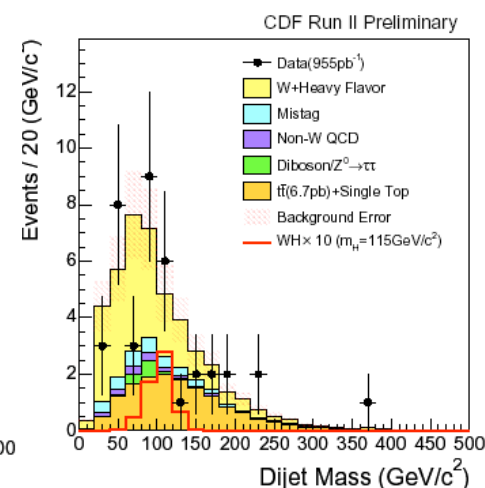
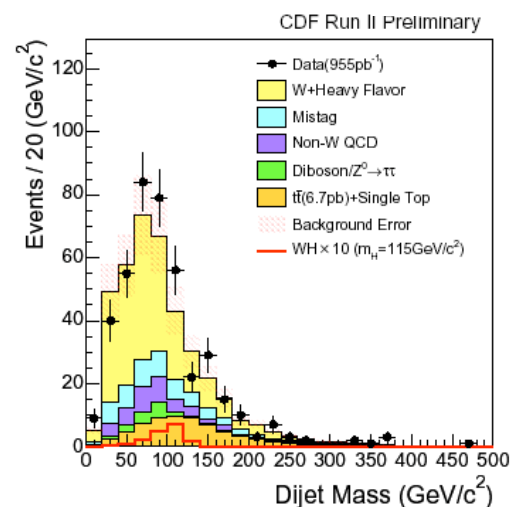
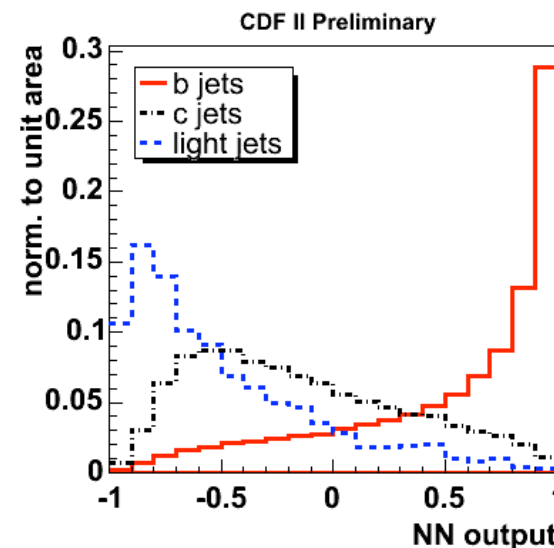
Limit / SM rate=25 (at $m_H=115 \text{ GeV}$)

$L=1 \text{ fb}^{-1}$

Higgs: $WH \rightarrow l\nu b\bar{b}$



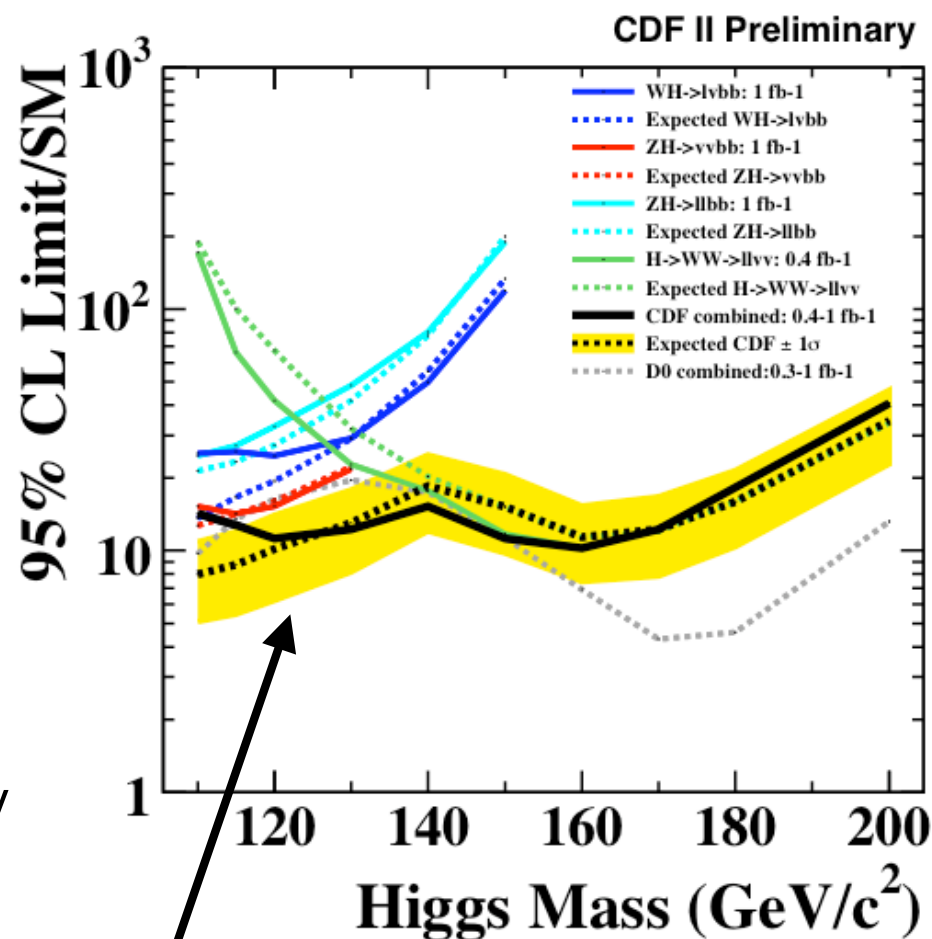
- Lepton, missing E_T and 2 jets:
 - One or two b-tags
- New since last year:
 - NN b-tagger
 - Include double-tag
 - Include full 1 fb^{-1} dataset
 - Luminosity equivalent gain:
 - $(S/\sqrt{B})^2 = 1.25^2 = 1.6$



Exp. Limit / SM rate = 23.0 (at $m_H = 115 \text{ GeV}$)

Higgs Boson: Combined Limits

- Combination of most sensitive CDF Higgs results:
 - $WH \rightarrow l\nu bb$ (1 fb^{-1})
 - $ZH \rightarrow \nu\nu bb$ (1 fb^{-1})
 - $ZH \rightarrow ll bb$ (1 fb^{-1})
 - $H \rightarrow WW$ (0.3 fb^{-1})
 - Results on ttH and $WH \rightarrow WWW$ not yet included
- Getting closer!
 - B_s mixing achieved sensitivity improvement by factor 4 just by improving experimental techniques

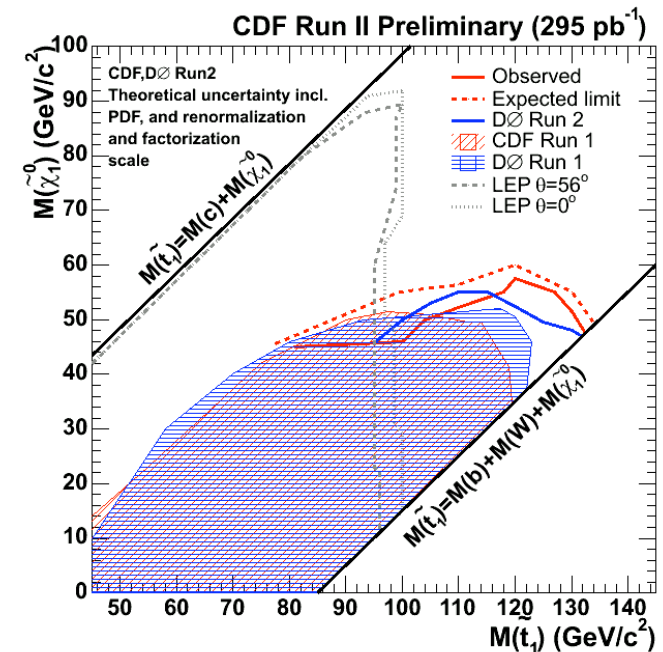
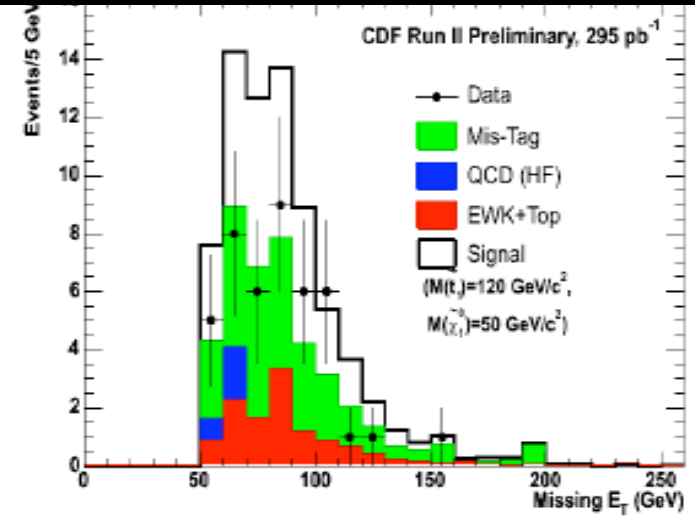
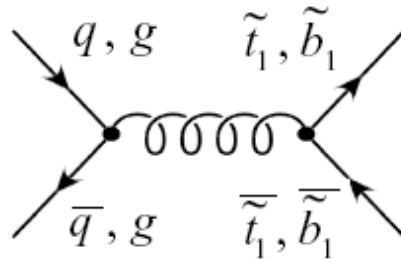


95%CL Limit / (SM @115 GeV): exp.=9, obs.=13

Beyond the Standard Model

SUSY: stop and sbottom

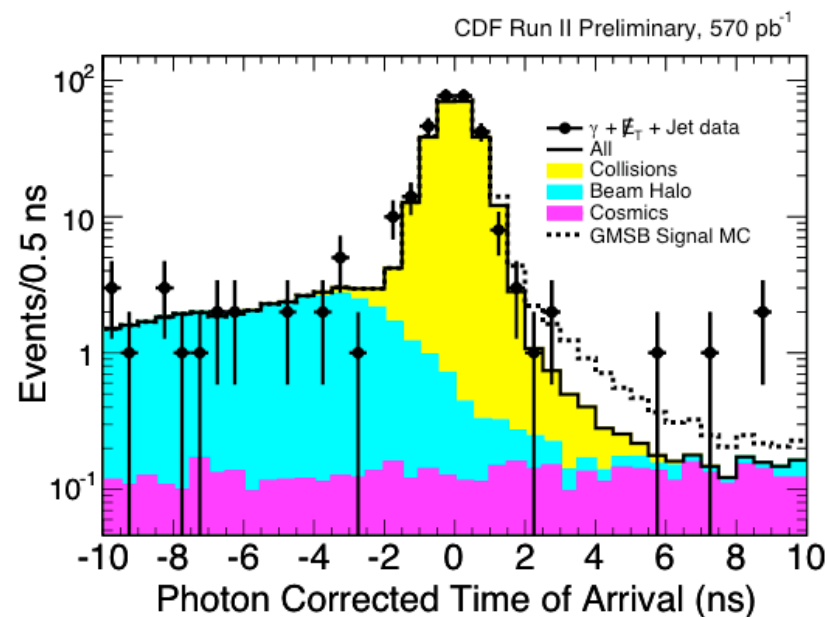
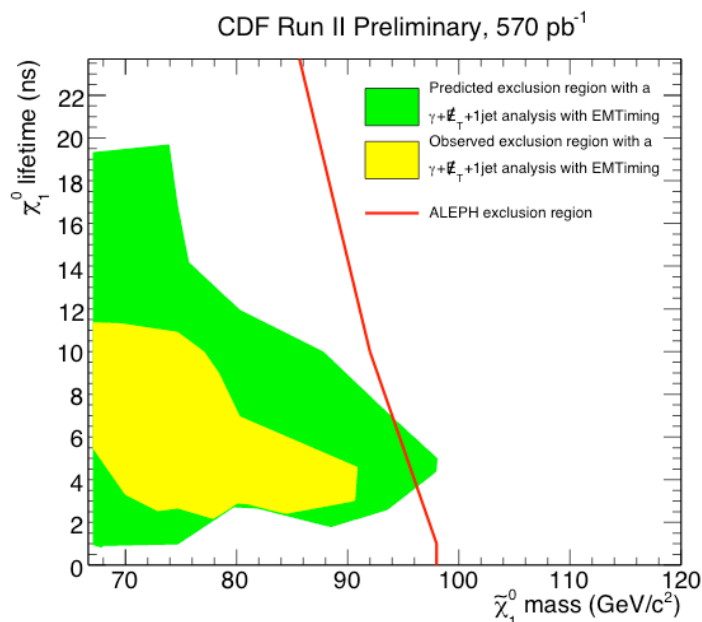
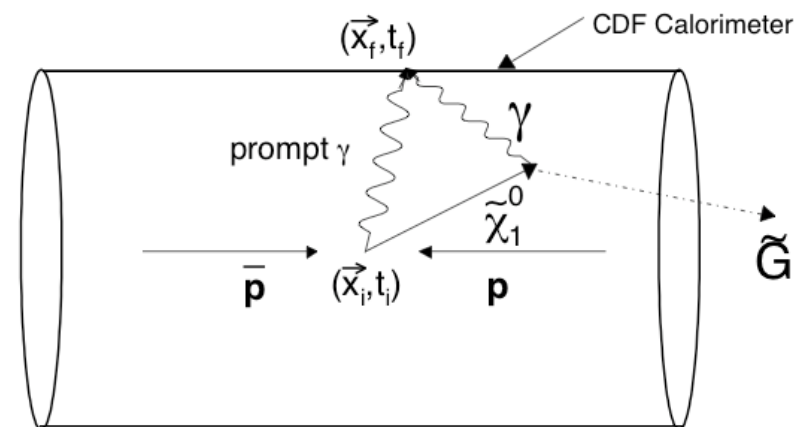
- Stop and sbottom quarks are the lightest squarks:
 - Produced via strong interaction
 - Large cross sections
- Here:
 - Stop: $t \rightarrow c\chi$
 - Sbottom: $b \rightarrow b\chi$
- Search for 2 c- or b-jets and large missing E_T
 - Tag heavy flavor using “jet probability” algorithm



Further constraining SUSY parameter space

GMSB SUSY: Delayed Photons

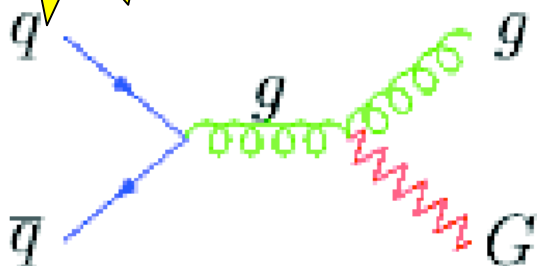
- Search for photon inconsistent with collision time:
 - From heavy long-lived object decay: GMSB SUSY
 - Use new EM timing device to measure photon arrival time



Constraining long-lived neutralinos up to $m=90 \text{ GeV}/c^2$

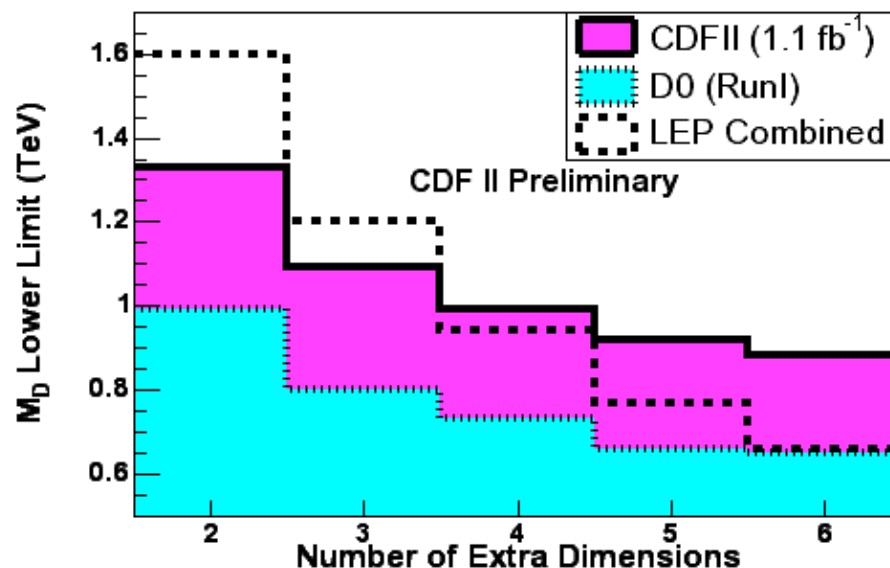
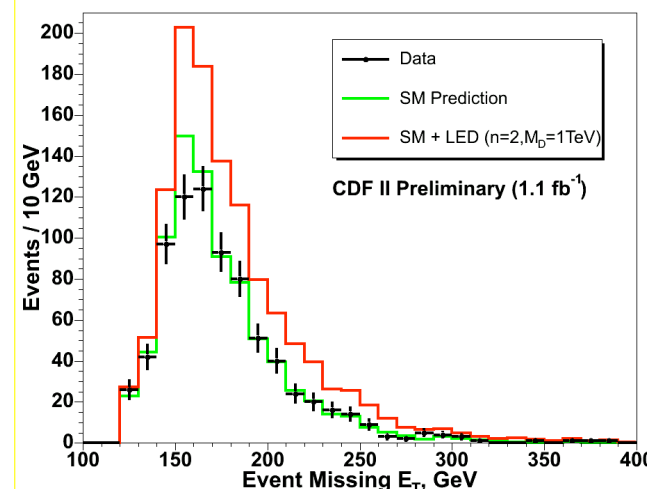
$L=1 \text{ fb}^{-1}$

Large Extra Dimensions



$$R^n = \frac{1}{8\pi} \left(\frac{M_{PL}}{M_D} \right)^2 \frac{1}{M_D^n}$$

- Extra Spatial Dimensions could solve the hierarchy problem:
 - Effective Planck scale is lowered
- Good signature:
 - Monojet = 1 jet + missing E_T
 - Main background $Z+\text{jet} \rightarrow \nu\nu+\text{jet}$ measured from data
- No evidence for Extra Dimensions

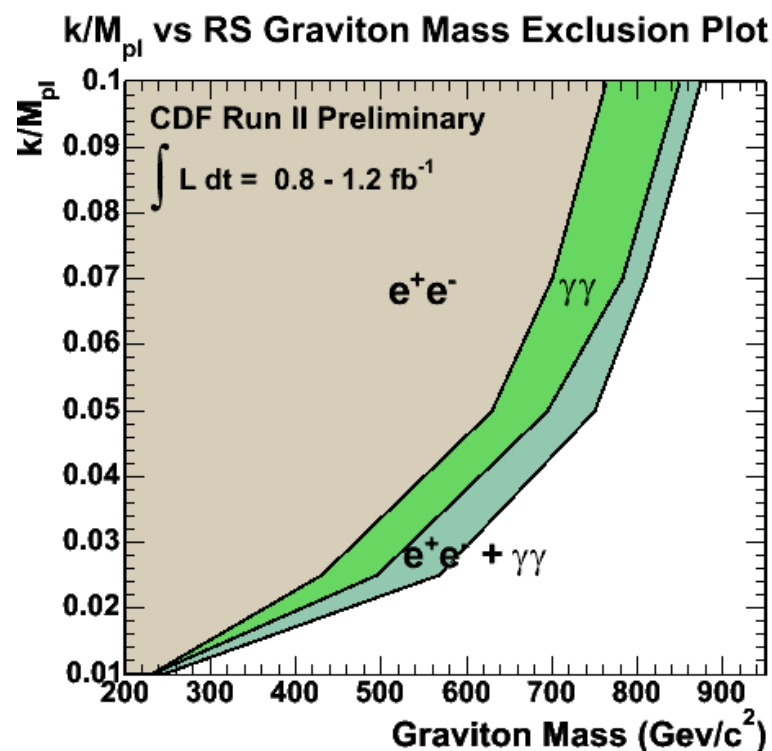
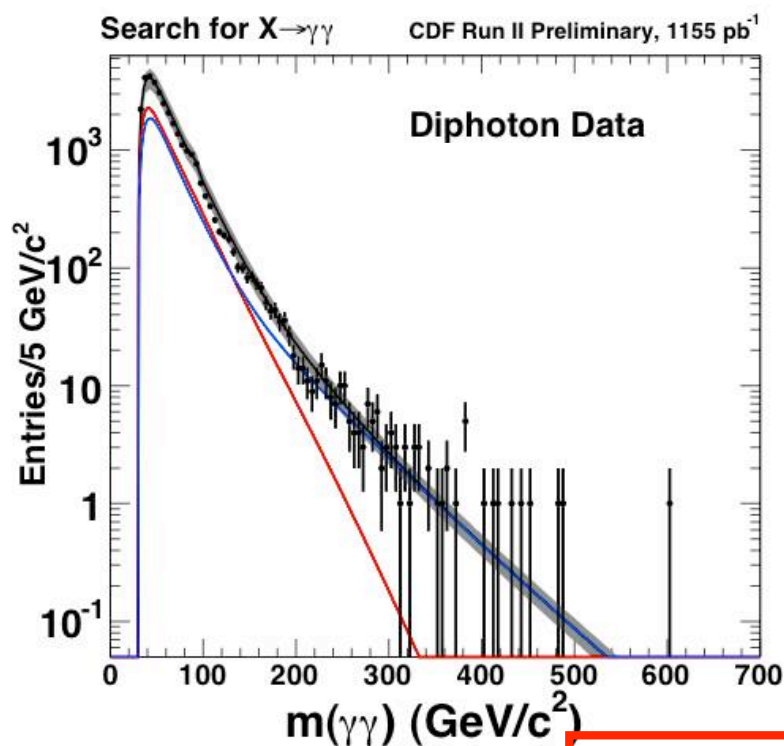
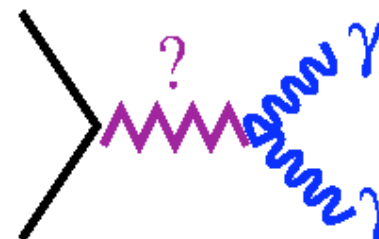


CDF has world's best sensitivity for >3 dimensions

$L=1 \text{ fb}^{-1}$

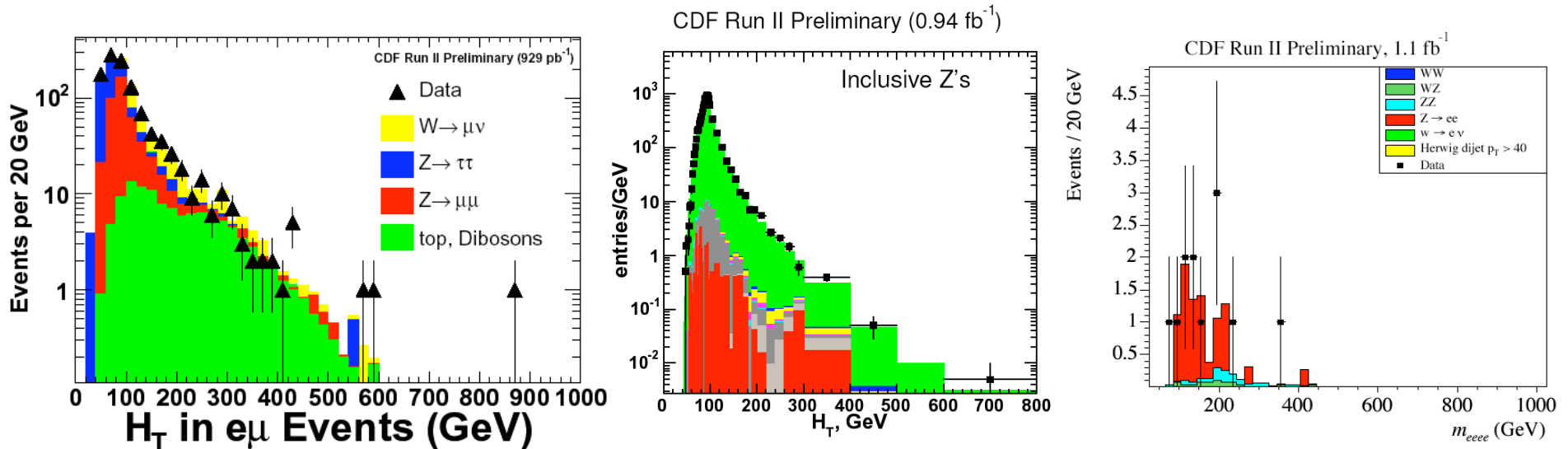
High Mass Diphotons

- Resonance in diphoton mass spectrum?
 - E.g. predicted in Randall-Sundrum model:
 - alternative ED model to solve the hierarchy problem
 - predicts $\gamma\gamma$ and ee resonances



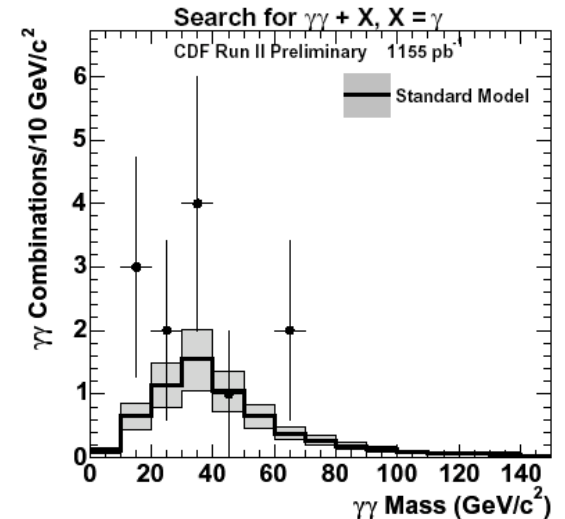
$M > 875 \text{ GeV}$ for $k/M_{\text{pl}} = 0.1$

Model-Independent Searches

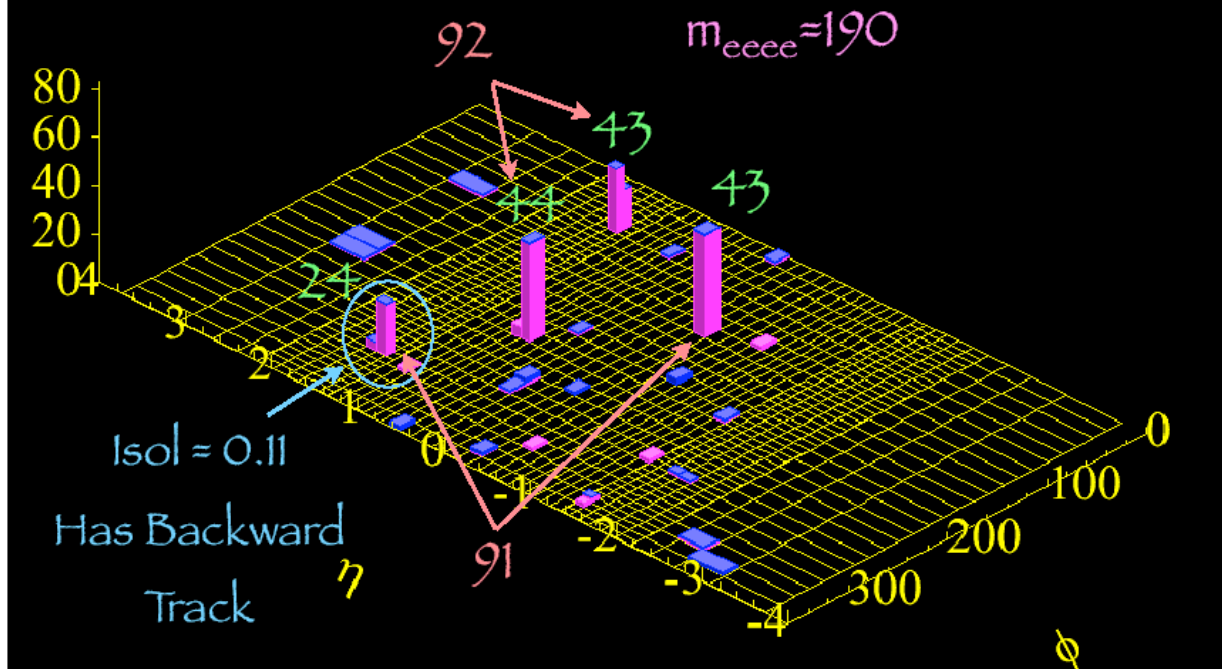


- New searches for anomalous production of:
 - W's and Z' at high H_T
 - Anomalous ZZ
 - Diphotons+X (X= γ ...more to come)
- A spectacular event at $H_T \sim 900$ GeV

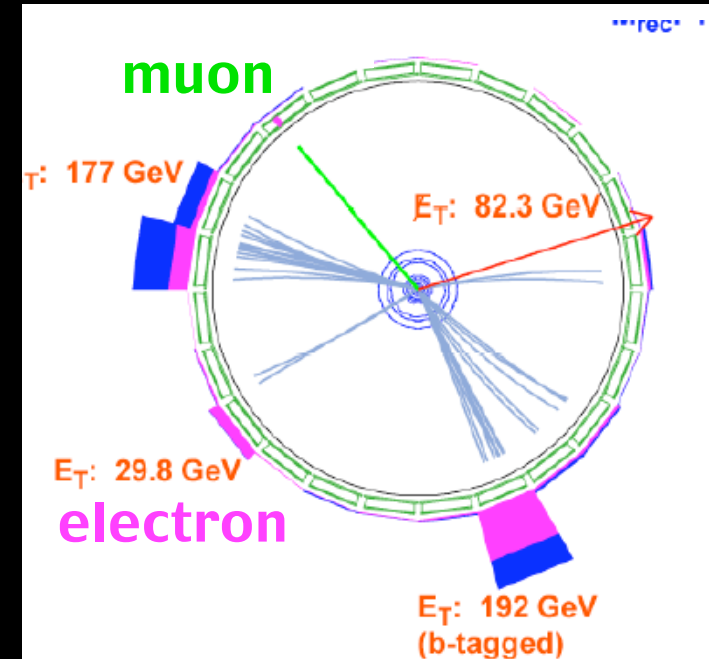
$L=1 \text{ fb}^{-1}$



Two Spectacular Events



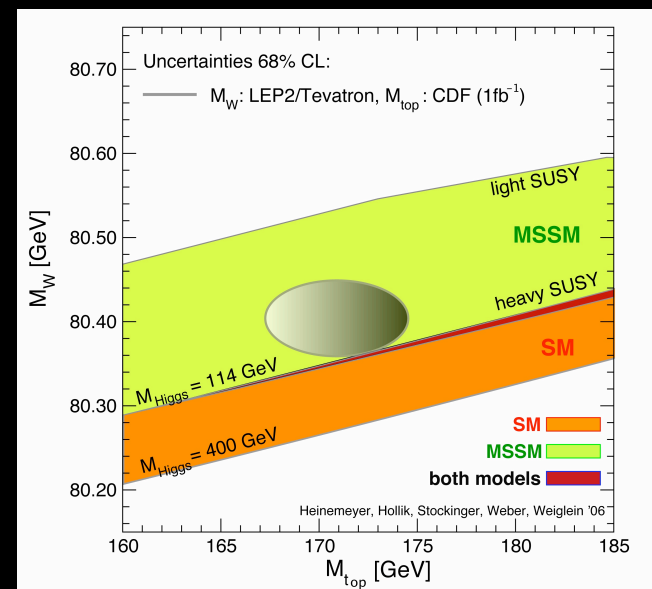
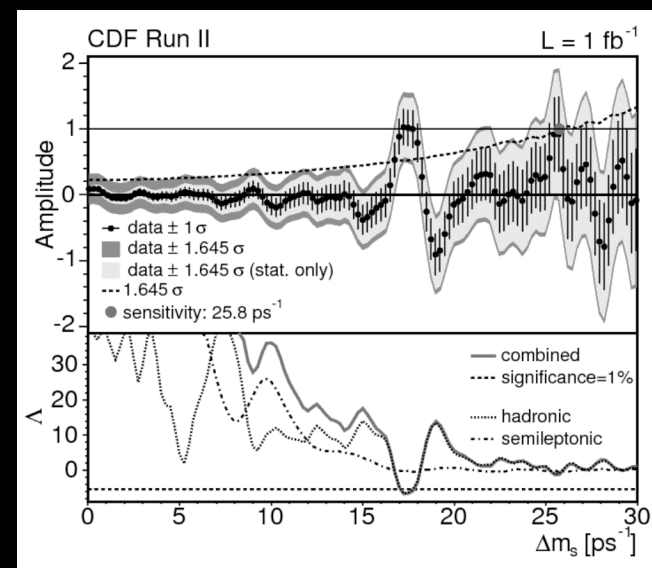
ZZ candidate



Top dilepton event?
 $H_T = 850 \text{ GeV}$

Conclusions

- Many new analyses using 1 fb^{-1} :
 - Only 5 months after end of data taking:
 - Searches and precision measurements
- Highlights:
 - B_s oscillation frequency
 - Precise top mass
 - Jet- and b-jet production
 - Searches for Higgs, SUSY and Extra Dimensions



Conclusions

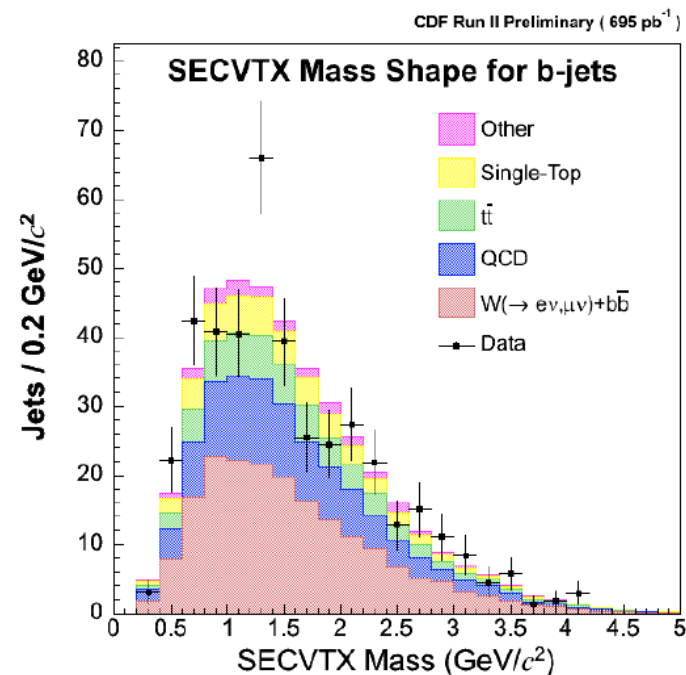
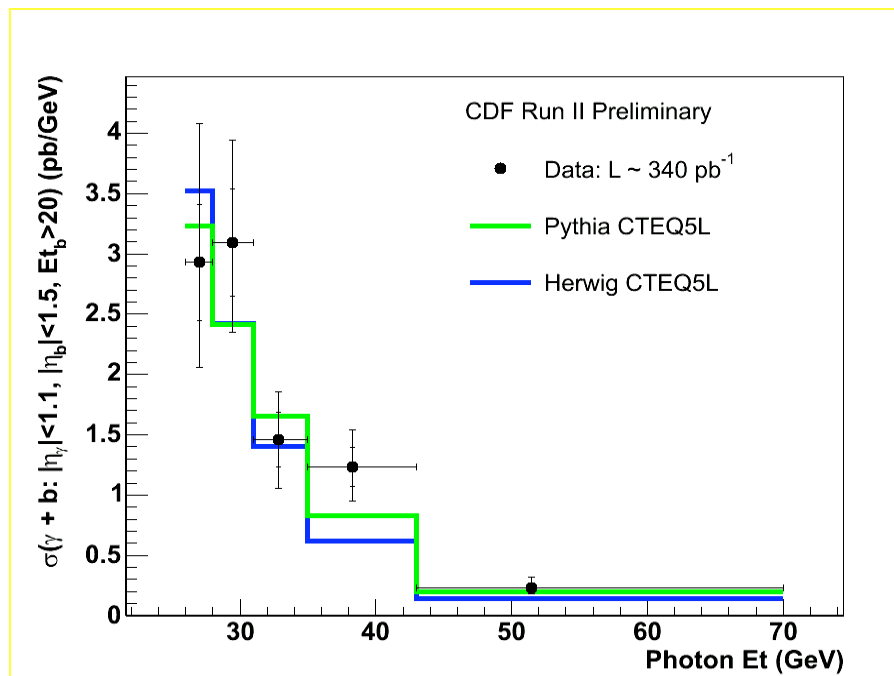


CDF keeps attacking the Standard Model vigorously

CDF is ready for Moscow



Photon+b-jets and W+b-jets



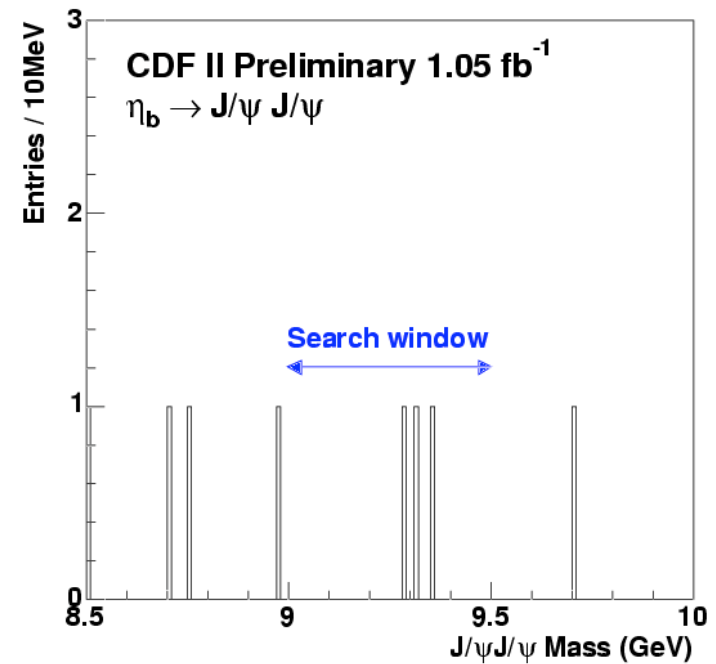
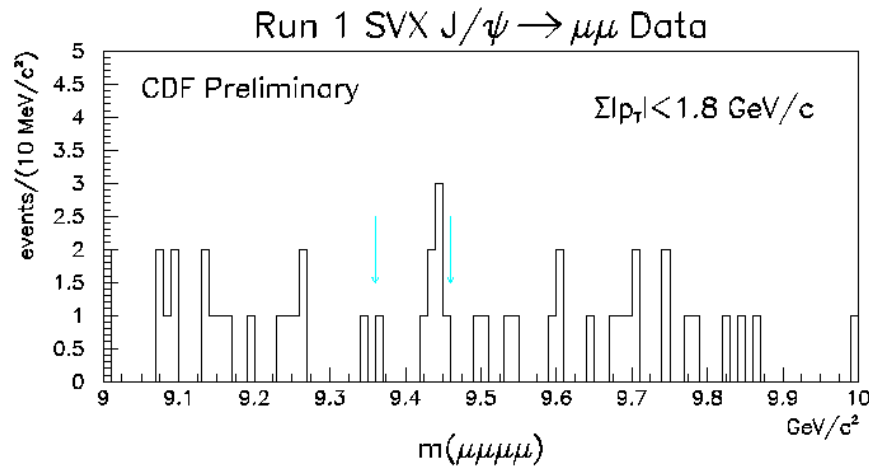
- First measurements of both these processes
- Data agree with LO QCD predictions:
 - No comparison to NLO calculation yet

	$\sigma(W+\text{jet}) \times \beta(W \rightarrow l\nu)^* \text{ [pb]}$
CDF	$0.90 \pm 0.20(\text{stat.}) \pm 0.26(\text{syst})$
Alpgen	0.74

*cuts: $p_T(l) > 20 \text{ GeV}$, $|\eta(l)| < 1.1$, $p_T(\nu) > 25 \text{ GeV}$, $E_T(\text{jet}) > 20 \text{ GeV}$, $|\eta(\text{jet})| < 2$

Backup

$\eta_b \rightarrow J/\psi J/\psi$



- Run 1 history (80 pb⁻¹):
 - 7 events observed, 1.8 background:
 - 2.2 sigma signal (~ pb)
 - Upper limit 18 pb
- Theoretical predictions:
 - Cross section x BR = 0.02 - 4 pb

- Run 2, L=1.05 fb⁻¹:
 - No signal
 - Upper limit 2.6 pb

$$\sigma(p\bar{p} \rightarrow \eta_b X) \cdot \beta(\eta_b \rightarrow J/\psi J/\psi) \cdot \beta(J/\psi \rightarrow \mu\mu)^2 < 2.6 \text{ pb}$$

W Boson Helicity

SM prediction of helicity fractions (assuming $M_t=175\text{GeV}$):

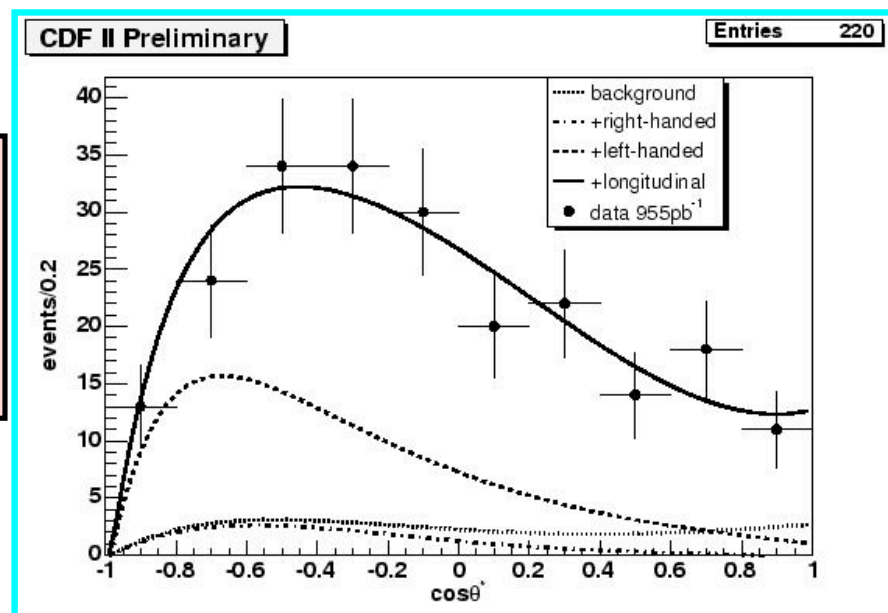
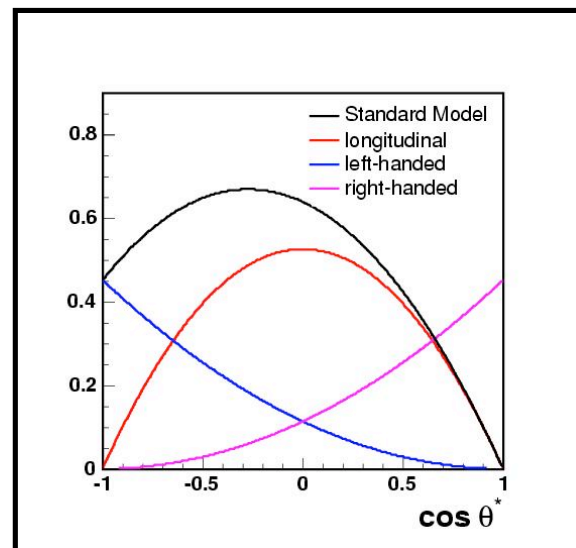
- **longitudinal $f_0 = 0.7$**
- **left-handed $f_- = 0.3$**
- **right-handed $f_+ = 0$**

$$\cos(\theta^*) = \frac{p_l \cdot p_b - E_l \cdot E_b}{|p_e||p_b|}$$

Result:

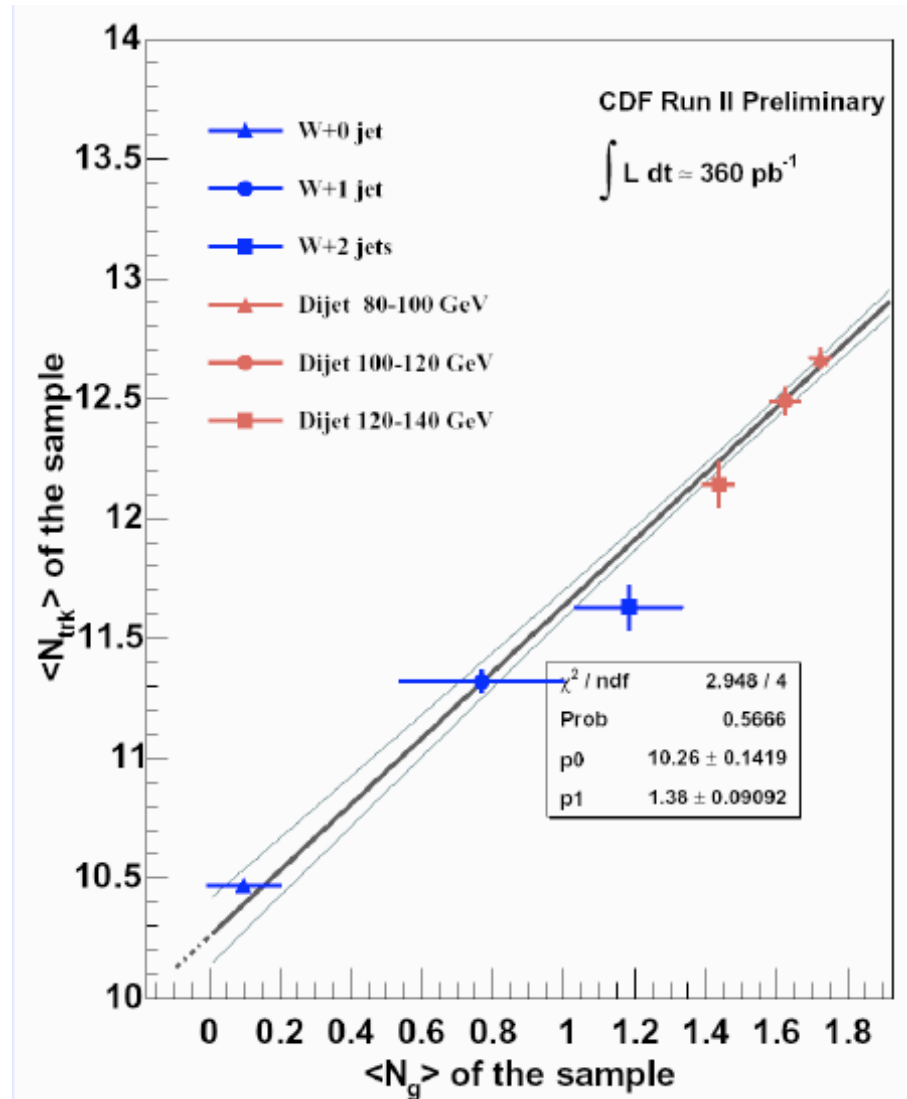
- $f_0 = 0.606 \pm 0.13$ (fixing $f_+ = 0$)
- $f_+ < 0.11$ @ 95% C.L

+ new karlsruhe analysis



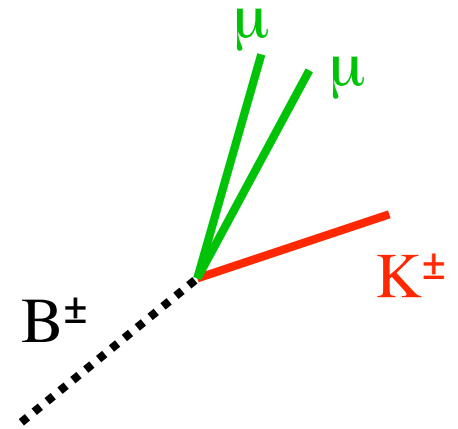
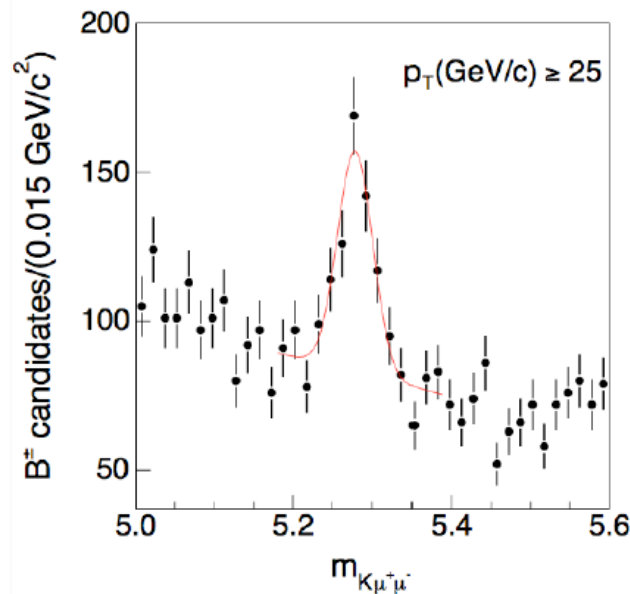
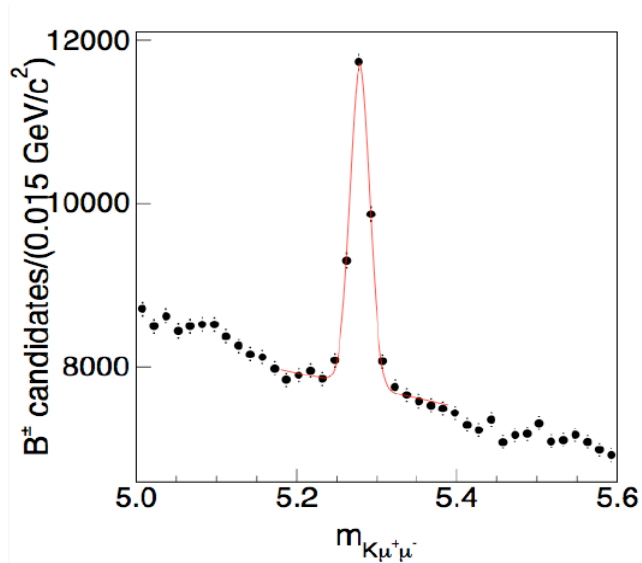
Top Production Mechanism

- NLO:
 - $Qq \rightarrow tt$: 85%
 - $Gg \rightarrow tt$: 15%
- Measure in data:
 - Use number of tracks to discriminate
 - Control in many samples:
 - Good correlation with gluon fraction



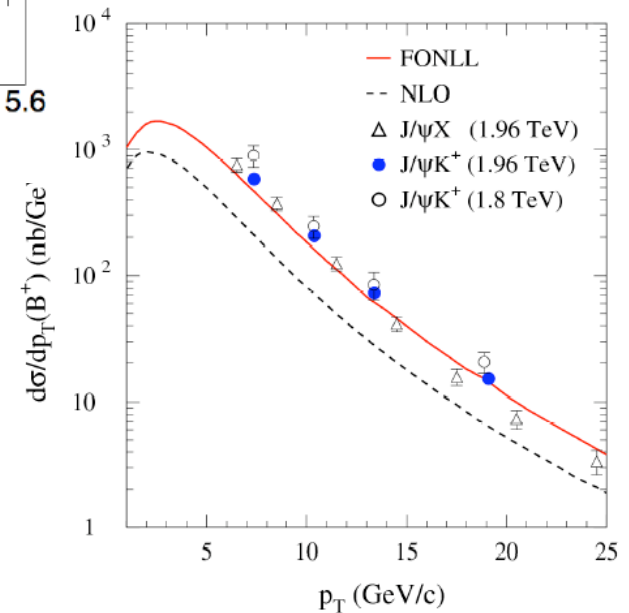
B^\pm Hadron Cross Section

B cand. = 8197 ± 239 # B cand. = 277 ± 44



- Select $B^\pm \rightarrow J/\psi K^\pm$ candidates:
 - 8197 ± 239 candidates in 740 pb^{-1}

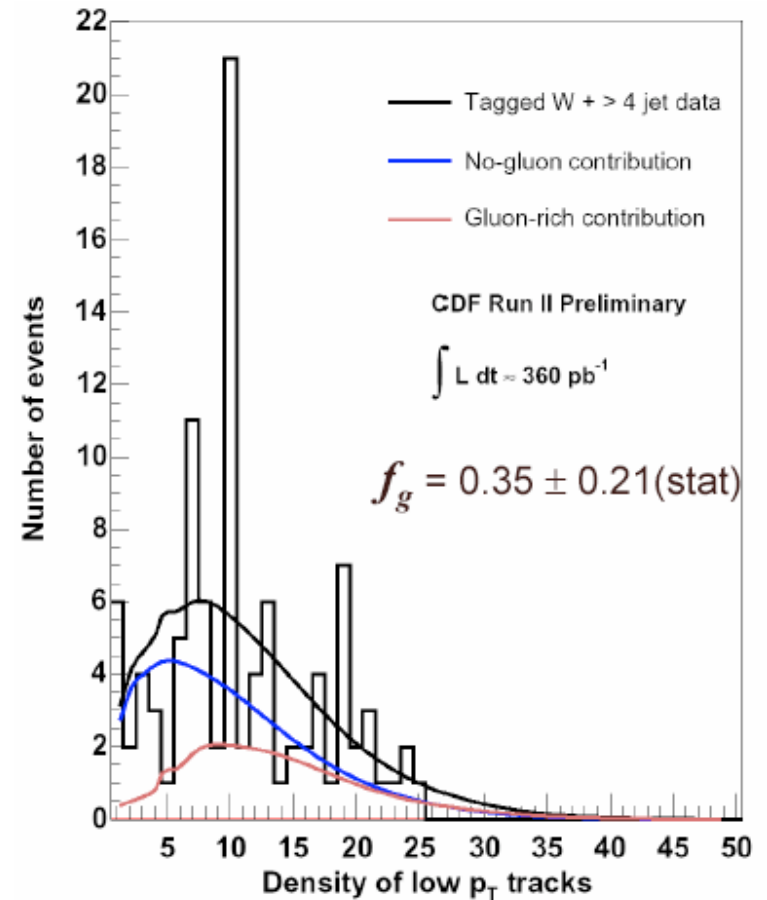
- Cross section agrees well with previous results and theory (FONLL)



Top Production Mechanism

- Need plot without fg
- Result

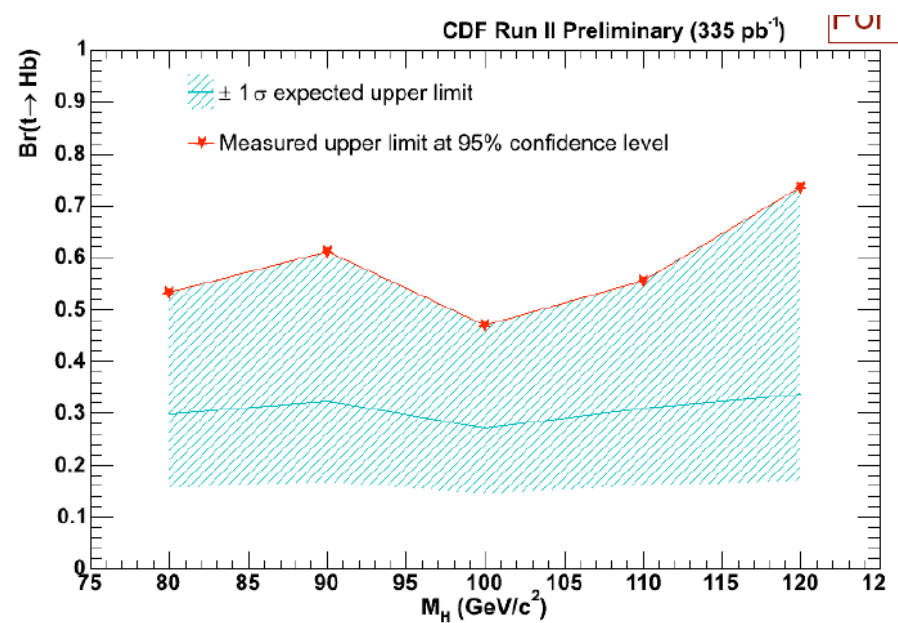
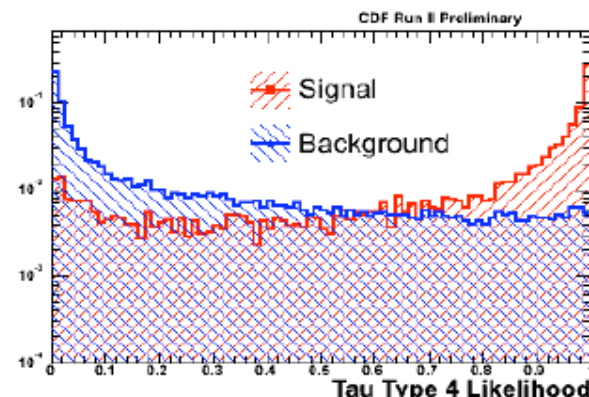
$$f_g^{tt} = 0.30 \pm 0.24(stat) \pm 0.08(syst)$$



$$\frac{\sigma(gg \rightarrow t\bar{t})}{\sigma(p\bar{p} \rightarrow t\bar{t})} = 0.27 \pm 0.23(stat) \pm 0.10(syst)$$

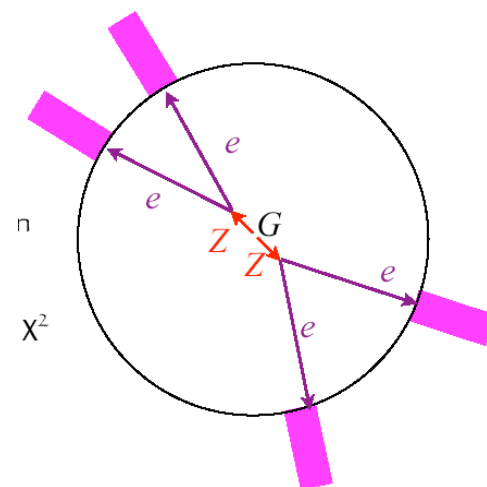
Tau's in ttbar events

- Search for $pp \rightarrow e/\mu + \tau + b + j + E_T + X$
 - Likelihood used to identify tau-leptons:
 - 4 categories
- Interpret in charged Higgs scenario

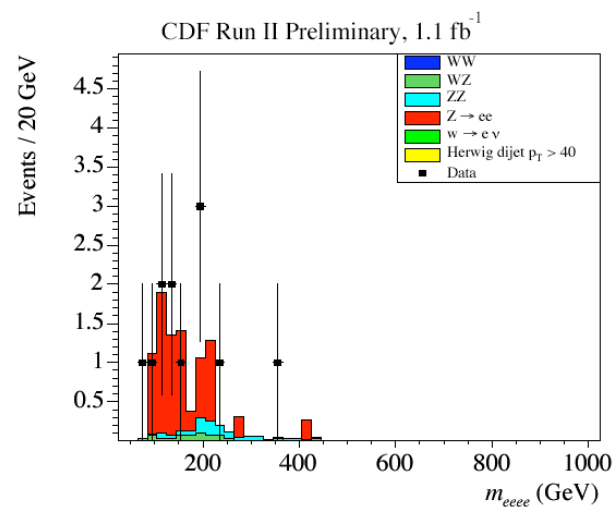
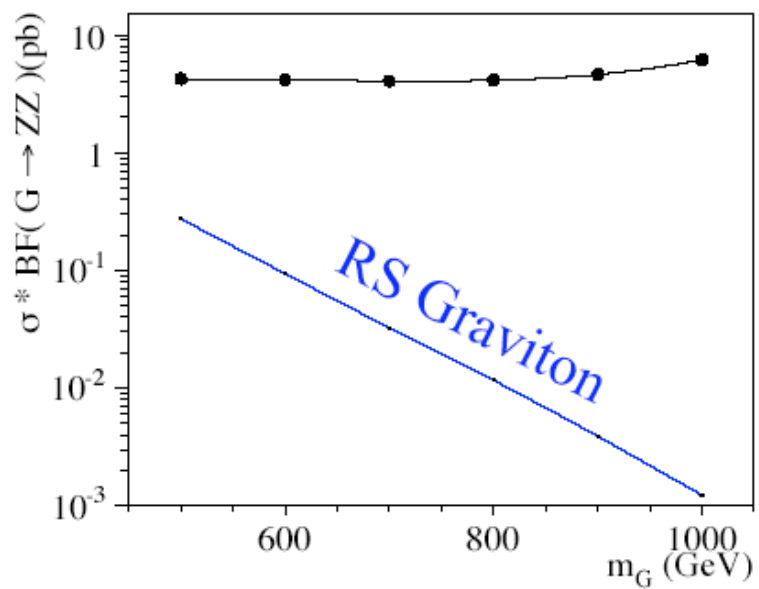


	Electron, Tau	Muon, Tau	All
$t\bar{t} \rightarrow \tau$	1.22 ± 0.22	0.85 ± 0.15	2.07 ± 0.37
fake τ , b -jet	0.65 ± 0.14	1.10 ± 0.22	1.74 ± 0.36
Other	0.03 ± 0.03	0.02 ± 0.02	0.06 ± 0.06
Total	1.90 ± 0.26	1.97 ± 0.27	3.88 ± 0.52
Data	4	2	6
Probability	0.13	0.58	0.20

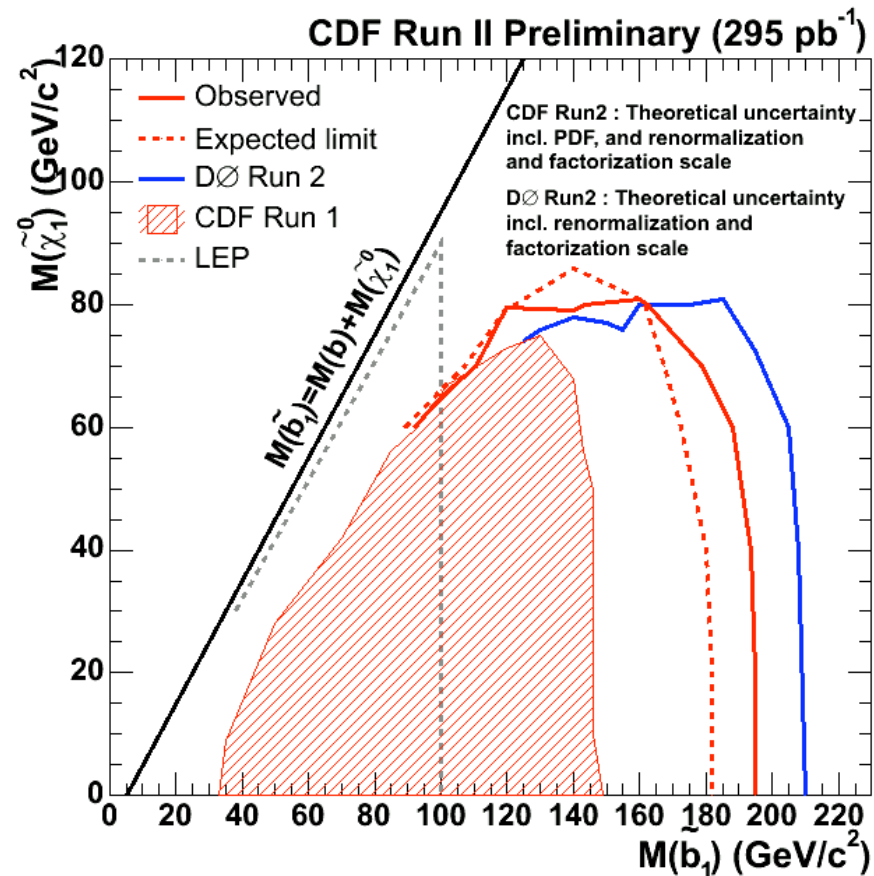
ZZ



CDF Run II Preliminary, 1.1 fb^{-1}

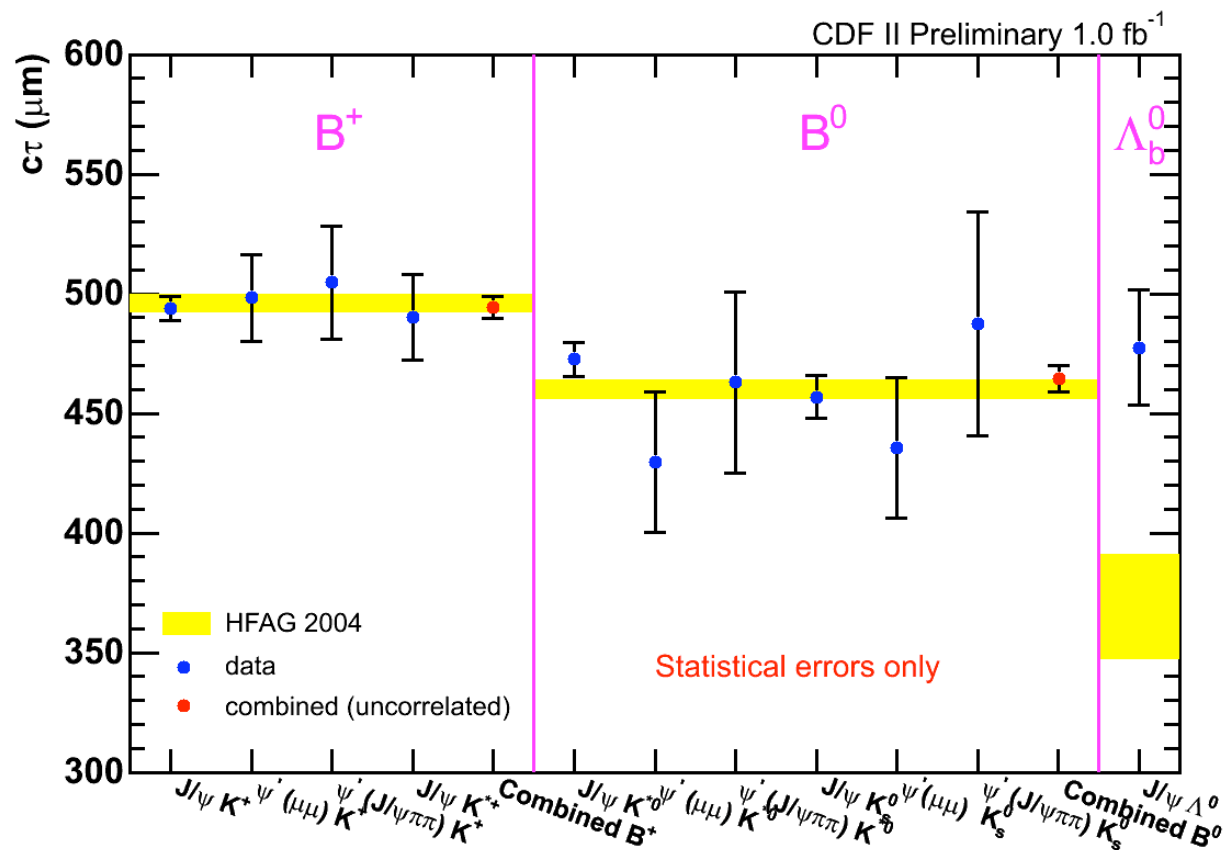


SUSY: stop and sbottom



- Extending exclusion region in both stop and sbottom mass plane

Λ_b Lifetime Cross Checks



- Cross checks in similar B^+ and B^0 decay channels:
 - Particularly important $B \rightarrow J/\psi K_s^0$